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Control of VOC Emissions from Polystyrene Foam Manufacturing

Radian Corp., Research Triangle Park, NC

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This document contains information on polystyrene foam manufacturing processes, associated emissions of volatile organic compounds, emission control methods, and cost estimates for emission control.

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Office of Air Quality Planning and Standards
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PREFACE

The purpose of this document is to provide technical information to States on estimating and controlling volatile organic compounds (VOC) emissions from the manufacture of polystyrene foam (PSF). This document addresses the expandable polystyrene bead industry, and the extruded polystyrene foam and sheet industries.

The Control Technology Center (CTC) was established by EPA's Office of Research and Development (ORD) and Office of Air Quality Planning and Standards (OAQPS) to provide technical assistance to State and Local air pollution control agencies. Three levels of assistance can be accessed through the CTC. First, a CTC HOTLINE has been established to provide telephone assistance on matters relating to air pollution control technology. Second, more in-depth engineering assistance can be provided when appropriate. Third, the CTC can provide technical guidance through publication of technical guidance documents, development of personal computer software, and presentation of workshops on control technology matters.

The technical guidance projects, such as this information document, focus on topics of national or regional interest that are identified through contact with State and Local agencies. In this case the CTC undertook the investigation of volatile organic compound (VOC) emissions and their control for the production of polystyrene foam. The document includes descriptions of the production processes used, associated emissions, available controls, and estimated costs for applying controls.

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1.0 INTRODUCTION

The purpose of this study was to conduct a survey of the polystyrene foam (PSF) manufacturing industry to characterize the industry, define the nature and scope of volatile organic compound (VOC) emissions from this source category, identify potential controls for reducing VOC emissions, and develop cost estimates for VOC capture and control technologies. The study includes an estimate of total industry VOC emissions and the geographic distribution of industry facilities. A process overview and descriptions of three separate manufacturing processes used for polystyrene foam products are presented in this report, and process emission points are identified. The report also includes a review of demonstrated and potential emission control options that have been identified for reducing VOC emissions from this source category. The estimates of VOC emissions are not based on empirical data, but were calculated based on figures and assumptions from industry and government reports. Cost estimates for capture and control of VOC emissions have been developed according to the U.S. Environmental Protection Agency's (EPA) Office of Air Quality Planning and Standards (OAQPS) Control Cost Manual, 1990.

Many previous studies of this source category have focused primarily on chlorofluorocarbon (CFC) rather than VOC emissions. However, with the adoption of the Montreal Protocol (40 CFR Part 82) in August 1988, which restricts the production and consumption of a number of fully halogenated CFCs, the use of hydrocarbons and soft CFCs as blowing agents in the polystyrene foam manufacturing process has increased.

This increased use of hydrocarbon blowing agents will likely result in increased VOC emissions from this source category nationwide. With the continued and increasing ozone non-attainment problems facing many U.S. metropolitan areas, EPA is evaluating the potential for reducing emissions from all sources of VOC. In 1988, 101 urban areas in the United States

were classified as non-attainment areas for ozone. It is estimated that over 170 polystyrene foam manufacturing plants are located in non-attainment areas. National annual VOC emissions from this source category are estimated at 25,000 short tons per year. Approximately 68 percent of source facilities identified in this report are located in ozone non-attainment areas. Therefore, the PSF industry represents a source of VOC emissions which may be affecting local air quality in many urban areas of the United States.

2.0 CONCLUSIONS

The major findings of this study are presented below. The conclusions can be categorized into three groups: 1) industry characterization, 2) VOC emissions and emission controls, and 3) control cost estimates. In general, due to the eventual phaseout of CFCs, it is expected that VOC emissions from this source category will increase over time unless emission control equipment is installed or alternative blowing agents are used. Add-on controls such as carbon adsorption and incineration have been demonstrated for this industry. In addition, some existing facilities have successfully switched from hydrocarbon blowing agents to hydrochlorofluorocarbon (HCFC) blowing agents. HCFCs have only a fraction of the ozone depletion potential of CFCs and are, for the present, considered an environmentally acceptable alternative to both hydrocarbon and CFC blowing agents. The PSF industry, however, considers the regulatory status of HCFCs uncertain, and other alternatives are being actively investigated.

2.1 INDUSTRY CHARACTERIZATION

- Polystyrene foam manufacturing consists of three separate processes for producing foam sheet, foam board, and expandable beads. Initial estimates indicate that the expandable bead process results in the greatest VOC emissions during processing, followed by foam sheet production. Extruded foam board is still primarily manufactured using CFCs as the blowing agent, and, therefore, VOC emissions are negligible;
- The polystyrene foam blowing industry is made up of many companies of widely varying sizes which purchase polystyrene or expandable polystyrene beads (EPS) and manufacture specialty foam products. These plants are spread geographically throughout the United States, and plants are located in 37 states;

- Polystyrene foam can be blown with a number of different blowing agents. Until the late 1980s, CFCs were the blowing agent of choice for extruded PSF products. Due to an eventual phaseout of fully halogenated CFCs, the industry is switching to HCFCs and hydrocarbons as alternative blowing agents. The EPS process continues to primarily use pentane as the blowing agent, while isopentane and n-butane are used occasionally.

2.2 VOC EMISSIONS

- National VOC emissions from polystyrene foam blowing in 1988 are estimated at 25,000 short tons per year;
- There are three general classes of emissions from polystyrene foam: manufacturing emissions; prompt foam cell losses, which are losses that typically occur during storage and shipping; and banked emissions, which are losses that occur through slow diffusion of blowing agents out of the foam over the life of the product. This report focuses on emissions during manufacturing, because they are significant and controllable. Less attention is given to emissions during storage and shipping. Banked emissions are characterized to some extent, but discussion is limited because no controls for banked emissions have been identified (except, of course, for manufacturing with alternate blowing agents);
- Exhaust streams from individual plants are typically characterized by high flow rates and low VOC concentrations due to OSHA regulations for minimizing worker exposure to pentane and ventilation systems design requirements to ensure that concentrations remain below 25 percent of the Lower Explosive Limit (LEL) to minimize fire and explosion hazards.

2.3 VOC EMISSIONS CONTROLS

- Incineration is a demonstrated and readily available add-on control technology for reducing VOC emissions from polystyrene foam blowing. Incineration can reduce captured VOC emissions by 98+ percent; however, the cost per ton of VOC removed can be relatively high due to the large exhaust flow rates and low VOC concentrations characteristic of the exhaust stream. PSF plants that have successfully incinerated emissions generally have

ducted the exhaust to existing boilers or other existing combustion devices, and have thereby eliminated the major capital expenses;

- Carbon adsorption also has been demonstrated as a VOC emissions control device for the PSF manufacturing industry. However, the VOC removal efficiencies are expected to be somewhat lower than removal efficiencies which can be achieved using incineration;
- Use of alternate blowing agents such as chlorodifluoromethane (HCFC-22), and tetrafluoroethane (HCFC-134a) in place of CFC and hydrocarbon blowing agents, or CO_2 in combination with hydrocarbons is increasing as a means of VOC and CFC emission reduction, particularly for sheet extrusion processes. Cost and availability of the alternate blowing agents are still problematic, although a significant portion of the PSF sheet extrusion industry has recently switched to using primarily chlorodifluoromethane (HCFC-22) as a blowing agent.

2.4 CONTROL COST ESTIMATES

Control costs have been estimated for PSF sheet and EPS bead processes for small, medium, and large capacity facilities. Carbon adsorption and thermal incineration are considered as control options. The resultant cost effectiveness figures are as follows:

Process	Foam Product Capacity (ton/yr)	Carbon Adsorption Cost ($/ton of pollutant removed)	Thermal Incineration Cost ($/ton of pollutant removed)
EPS Bead	1,500	3,300	6,950
	3,000	2,010	5,020
	4,500	1,405	4,405
PSF Sheet	1,000	6,790	11,100
	5,000	2,190	5,055
	10,500	1,290	4,050

3.0 INDUSTRY STRUCTURE

Polystyrene foam (PSF) products are manufactured by one of two basic processes, extrusion or expandable bead blowing. Both of these manufacturing processes are described in detail in Section 4.0. Foam extrusion and expandable polystyrene (EPS) bead blowing each produce distinct end products, and involve distinct populations of manufacturing companies. This section of the report describes the products manufactured from PSF, the companies that produce PS and finished PSF products, and recent market trends.

3.1 END PRODUCTS

In general, PSF products are used for various packaging and/or insulation purposes. The density, strength, formability, and insulating qualities of PSF make it an ideal material for the familiar packing "peanuts," hamburger boxes, and hot or cold drink cups. A 1988 estimate of end uses for polystyrene resin indicates that extruded foam board products account for 11 percent, single service extruded sheet products account for 25 percent, all other sheet 22 percent, and EPS products account for 41 percent of total U.S. PSF production (approximately 1354 million lb/yr). Total PSF production in turn accounts for approximately 26 percent of total polystyrene use.[1]

3.1.1 Extruded Products - Boardstock and Sheet

Extruded PSF products include those made from foam board and foam sheet. Market figures for 1988 from the Journal of Modern Plastics indicate that about 60 percent of PSF products are extruded.[2] The vast majority of PSF board is used as insulation material in commercial and residential construction. Foam board is somewhat higher than fibrous glass in insulating efficiency and comparable in cost in dollars per R-factor (heat-resistance factor), and is also practical in certain construction designs where traditional insulating materials are not.

Extruded PSF insulation has high resistance to moisture and to freeze/thaw damage and, consequently, retains its insulating quality longer than other foam insulation materials. It is particularly well suited to insulating around building foundations.[3] Some PSF board is laminated with facing materials that increase the board's moisture resistance and retain the insulating capabilities (i.e., the blowing agent) longer.

Foam sheet products are used largely for packaging, most notably for food packaging and single service packaging. The most familiar examples of foam sheet products are fast food containers, meat and produce trays used in grocery stores, and disposable plates. Table 3-1 lists the major end uses of PS foam board and sheet and presents total U.S. consumption of polystyrene foam products in 1987 and 1988.

3.1.2 Expandable Bead Products

Expandable polystyrene (EPS) beads are primarily used for foam board and sheet, foam packaging parts, and foam cups and containers as shown in Table 3-1. Most EPS beads are sold in bulk to foam processing companies who expand the beads to the required density and mold them in "steam chest" molds. About half the PSF insulating board is produced from the extruded process and half from the blown bead process. Physical properties such as thermal retention and dimensional stability are about equivalent at comparable densities.[4] However, EPS insulation board is considerably less expensive than extruded PS board or polyurethane board. Blown bead insulation board is used primarily in large commercial roofing applications and exterior wall systems.

PSF packaging materials include loose fill, such as "shells" and "peanuts," as well as molded shapes such as those that protect audio equipment during shipping. Loose fill, or dunnage, is manufactured with a combination of extrusion and EPS operations.

3.1.3 Substitute and Competing Products

For most extruded and expandable bead PSF products there are competing products. However, there are trade-offs in performance, such as insulation properties for heat retention, and environmental concerns such as recyclability to be considered. For example, PSF sheet is used for fast food packaging primarily by McDonald's Corporation. Other fast food operations, such as Wendy's, Arby's, and Burger King use various plastic or

TABLE 3-1. DOMESTIC CONSUMPTION OF POLYSTYRENE FOAM BY END USES[5]

	1987 (mill. lbs.)	1988 (mill. lbs.)
Extruded Foam		
Board	142	147
Sheet		
Single Service Containers	285	344
Stock Food Trays	188	190
Egg Cartons	80	80
Other Foamed Sheet	61	35
Subtotal Sheet	614	649
Total Extruded Polystyrene	756	796
Expandable Beads		
Building and Construction[a]	173	170
Cups and Containers	160	166
Packaging	80	106
Loose Fill	42	60
Other EPS Products	68	56
Total EPS Bead Products	523	558

[a]Figures include construction uses other than insulation board, such as wall and ceiling coverings and concrete filler.

foil laminated paper products for wrapping food; the cost is approximately equivalent for all of these wrapping options. Different companies choose different wraps, based on effectiveness, perceived attractiveness, or consumer appeal.[6] Egg cartons are manufactured from PSF sheet or from paper. Recent aggressive marketing by the paper industry has resulted in increased competition between paper and PSF sheet manufacturers of egg cartons. Recently, PSF waste disposal has become an important issue. Concern over landfilling and harm caused to marine mammals have received a certain amount of consumer attention and could affect competition. Industry is beginning recycling efforts for PSF products.

Foam insulating materials have become popular in construction since the early 1970s. However, polyurethane/polyisocyanurate and other products such as phenolic and fibrous glass board are still more commonly used than PSF for this purpose. Because of its superior moisture resistance, PSF insulation board has advantages over other insulation boards for below grade insulation.

3.2 MAJOR MANUFACTURERS OF PSF

3.2.1 Polystyrene Producers

Polystyrene is the raw material for extruded PSF products. About 20 to 25 percent of polystyrene resin produced is used in foam products. Relatively few large chemical companies produce the polystyrene polymer. Most extruded PSF products are also manufactured by these large polystyrene producers. Blowing agent is incorporated into the polystyrene as it is extruded. Expanded polystyrene products, however, are made from polystyrene beads, which contain an inactive blowing agent. These beads are usually produced by the large chemical companies, but they are expanded and molded at different facilities, as described in the following section. Table 3-2 lists the major U. S. producers of polystyrene resin and the estimates from three sources of their respective annual capacities for polystyrene production. Note that these figures for polystyrene production include resin used for some products other than foam products.

3.2.2 Foam Blowers

In some cases, PSF products are manufactured by the PS producing companies. However, most PSF facilities do not produce PS. These companies purchase PS and EPS beads as raw materials from PS producing

TABLE 3-2. ESTIMATED U. S. PRODUCTION OF POLYSTYRENE RESINS

Company	Plant Location	Directory of Chemical Producers 1989[a]	Chemical Marketing Reporter June, 1988[b]	Nannsville Chemical Products Synopsis April, 1988[c]	Average of Available Data
A & E Plastics	City of Industry, California		55		55
American Petrofina, Inc.	Calumet City, Illinois	200	200	200	200
	Carville, Louisiana	180	170	340	230
	Windsor, New Jersey	135	140	100	125
American Polymers, Inc.	Oxford, Massachusetts	106	80	70	85
Amoco Corporation	Joliet, Illinois			260	260
	Decatur, Alabama	203	210		207
	Torrance, California	30	25	35	30
	Willow Springs, Illinois	77	75	85	79
ARCO Chemical Company	Monaca, Pennsylvania	545	560	560	555
	Painesville, Ohio		70	70	70
BASF Corporation	South Brunswick, New Jersey	180	220	175	192
Chevron	Marietta, Ohio	480	440	440	453
Dart Container Corporation	Owensboro, Kentucky	70	70	65	68
Dow Chemical U.S.A.	Gales Ferry, Connecticut	100	130	100	110
	Ironton, Ohio	200	200		200
	Joliet, Illinois	210	215	200	208
	Midland, Michigan	400	400	335	378
	Pevely, Missouri	120	120	100	113
	Torrance, California	200	150	200	183
General Electric-Huntsman Corp.	Selkirk, New York	70		100	85
Goodson Polymers, Inc.	Troy, Ohio	110	80	78	89
Huntsman Chemical Corporation	Belpre, Ohio	300	300	320	307
	Chesapeake, Virginia	400	400	445	415
	Peru, Illinois	378 [d]	250	220	283
	Rome, Georgia	45	33	40	39
Kama Corporation	Hazleton, Pennsylvania	35	35	37	36

TABLE 3-2. (Continued)

Company	Plant Location	Directory of Chemical Producers 1989[a]	Chemical Marketing Reporter June, 1988[b]	Mannsville Chemical Products Synopsis April, 1988[c]	Average of Available Data
Mobil Corporation	Holyoke, Massachusetts	80	80	80	80
	Joliet, Illinois	365	360	360	362
	Santa Ana, California	70	60	60	63
Monsanto Company	Addyston, Ohio	300[d]	210	300	270
Polysar Group	Akron, Ohio	120	84		102
	Copley, Ohio			140	140
	Decatur, Alabama	140	70	70	93
	Leominster, Massachusetts	180	126	180	162
	Springfield, Massachusetts	180	210	300	230
Scott Paper Company (Plant formerly owned by Texstyrene)	Fort Worth, Texas	90	100	120	103
Tenneco, Inc.	City of Industry, California	55	55	55	55
Vititek	Delano, California		5	5	5
TOTAL:					6329

[a] SRI estimates as of January 1, 1989. SRI International. Directory of Chemical Producers. 1989. p. 900-901.
[b] Chemical Profile. Chemical Marketing Reporter. June 20, 1988. p. 74-75.
[c] Based on announced capacities and trade estimates. Mannsville Chemical Products Corporation. Chemical Products Synopsis: Polystyrene. April, 1988.
[d] 150 million pounds of capacity on standby.
[e] Plant is leased to Polysar, Inc.

Note: These production figures include resin used for some products other than foam products.

companies. This is especially true in the case of EPS beads. Those PSF facilities which purchase rather than produce PS for use in foam manufacturing tend to be smaller facilities and may specialize in custom molding such as foam packing for appliances. These foam blowing companies are more difficult to count and characterize, since they are so varied and are not tracked by economic analyses of the industry, as are the large chemical companies.

Several trade associations represent these various foam blowing companies and suppliers. The largest and most widely recognized association is the Society of the Plastics Industry (SPI). SPI represents hundreds of companies from all parts of the plastics industry; PS and PSF are the focus of only one of many divisions within SPI. The Foodservice and Packaging Institute, formerly the Single Service Institute, is an example of a specialized association serving plastic foam producers almost exclusively. There are also trade associations for the packaging industry that represent the PSF sheet producers in particular.

The number of PSF producers was estimated by compiling trade association membership lists, listings in the Thomas Register, and another published list of foam blowing companies. Table 3-3 gives the number of foam blowing companies located in each State that are listed in at least one of the table's references. The three references used to compile this table show very little overlap; therefore, it is difficult to gauge the completeness of this list. Appendix A lists many of these companies and their locations. Foam product manufacturers tend to cluster around urban areas and manufacturing centers where packaging material is in demand. Over two-thirds of the PSF manufacturing facilities listed in Appendix A are located in ozone non-attainment areas.

3.3 ECONOMICS OF THE PSF INDUSTRY

Available analysis of the PSF industry focuses on the production of PS and EPS beads. In the late 1980s, current journal articles note a surge in the demand for and production of PSF in general.[10,11] The surge has been constrained by a shortage in the PS supply, and complicated by aggressive competition from the polyurethane foam and paper industries.

The trade journal Modern Plastics predicted a stabilization of the PSF market during 1989. Growth has been at about 2 percent in 1989 following an average growth of 3.5 percent per year from 1978 to 1987. For

TABLE 3-3. DISTRIBUTION OF PSF PRODUCERS BY STATE

Sheet, Film, Board, and Block Producers Including Foam Blowers and Extruders[7,8,9]

State	Number of Facilities	State	Number of Facilities
Alabama	2	Mississippi	14
Arizona	1	Missouri	9
Arkansas	7	Nebraska	2
California	23	New Hampshire	1
Colorado	4	New Jersey	9
Connecticut	7	New Mexico	1
Florida	6	New York	14
Georgia	11	North Carolina	4
Hawaii	1	Ohio	14
Idaho	1	Oklahoma	1
Illinois	12	Pennsylvania	19
Indiana	5	Rhode Island	2
Iowa	2	South Carolina	2
Kansas	1	Tennessee	3
Kentucky	4	Texas	8
Maryland	3	Virginia	4
Massachusetts	12	Washington	6
Michigan	14	Wisconsin	5
Minnesota	3		
		TOTAL	237

1989 to 1992, average PSF industry growth is predicted to be 3 to 4 percent per year. Four key U.S. producers plan to increase production of EPS beads in order to meet predicted demand. This increased production capacity is expected to stabilize the PS market further.[12]

The price of polystyrene resin determines the price of finished PSF products. Resin price, in turn, is dependent upon the price of benzene and ethylene, the major raw materials used to produce PS. Prices of these raw materials were predicted to rise early in 1989.[13] However, efforts by major producers to restrain rising costs of PS are likely to be effective; the producers are concerned that higher PS prices would cause a switch to competing products.

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4.0 POLYSTYRENE MANUFACTURING PROCESSES

4.1 PROCESS HISTORY AND OVERVIEW

The three primary forms of PSF are extruded sheet, extruded board, and molded EPS. The production of PSF has been developed through a number of processes over the last 45 years. The oldest commercially available form is PSF board, first marketed by the Dow Chemical Company around 1943 under the trade name Styrofoam™. Foam sheet was introduced in the mid 1960s, and immediately found widespread use in the packaging industry.

Polystyrene is foamed through the use of physical blowing agents. Physical blowing agents are gases or liquids which are soluble in the molten polymer under pressure. Upon depressurization, the blowing agent volatilizes, causing the polymer to foam through the formation of gas cells.

Initially, PSF was produced with volatile hydrocarbon blowing agents such as n-pentane, isopentane, and n-butane. These blowing agents pose a safety risk due to their highly flammable nature, and began to gradually be replaced with nonflammable CFCs. Recent regulations prompted by widespread concern over depletion of the stratospheric ozone layer due to the use of CFCs have caused some major producers of PSF to reevaluate their commitment to the use of CFC-11 and CFC-12, and investigate a return to hydrocarbon blowing agents or other alternatives such as HCFC-22. Currently, extrusion and EPS bead molding account for virtually all PSF product manufacturing. These two processes and their respective blowing agents are described in detail below.

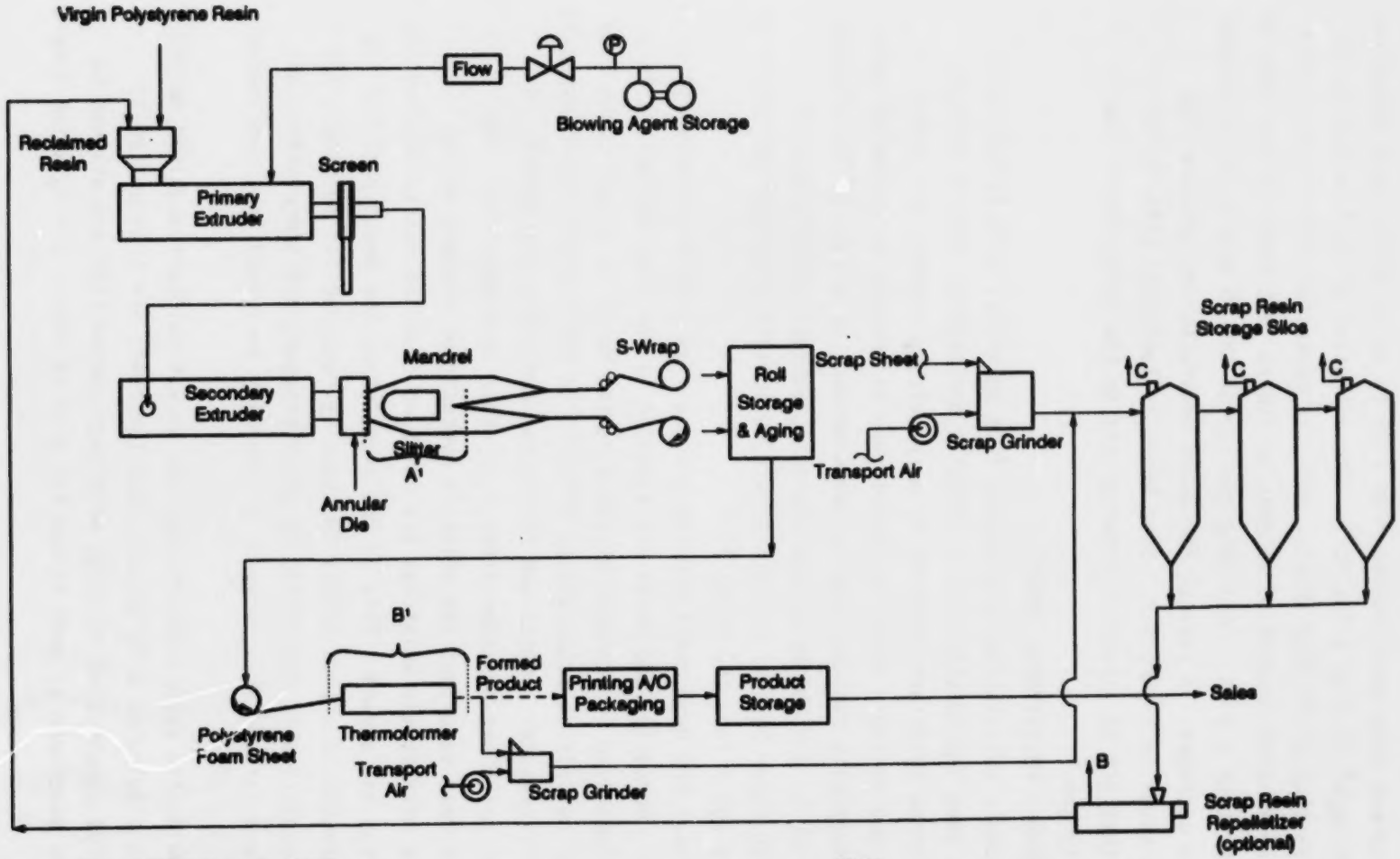
4.2 EXTRUDED POLYSTYRENE FOAM SHEET

The formation of PSF sheet is an extrusion process, commonly using two extruders in series or one extruder with two sections. The process produces foam sheets 1 to 7 mm thick, with densities of 32 to 160 kg/m^3 (2 to 10 $lbs/ft.^3$)[1] A typical extruded PSF foam sheet manufacturing process

flow diagram is shown in Figure 4-1. Polystyrene pellets are mixed with a small amount (0.2 to 2 percent) of powdered nucleating agent such as talc, or a combination of citric acid and bicarbonate of soda.[2] This mixture is fed into the primary extruder. The extruder is heated to provide an increasing temperature profile along its length, so that the polystyrene melts. The blowing agent is injected as a liquid, under high pressure, into the primary extruder where it mixes with the molten polystyrene. A screen is used to remove impurities from the molten polystyrene before it enters the secondary extruder. The secondary extruder introduces a cooling profile that increases the mixture's viscosity and gives it enough strength to contain the blowing agent as it expands. As the viscous polystyrene mix leaves the secondary extruder through a die, it foams and partially solidifies. The blowing agent bubbles attach to the nucleating agent, and a cellular structure is formed.

An annular extrusion die is used in extruded polystyrene sheet production, resulting in a tubular form. Foaming initiates near the die outlet where the pressure rapidly decreases, allowing the blowing agent to volatilize. As the foamed polystyrene passes through the die, compressed air is applied, forming a skin on the outer surfaces. Additional foaming occurs outside the die as the polystyrene tube passes over a forming mandrel, which determines the final circumference of the foam tube. At the end of the mandrel, the tube is slit lengthwise, flattened out, and an S-wrap, or sheet wrapping unit, winds the sheet into a roll. The PSF sheet is then stored for two to five days. During this time, a portion of the blowing agent diffuses out of the foam cells and is replaced with air. This results in an optimum ratio of air to blowing agent within the foam cells, which will allow for postexpansion of the PSF during reheating, before thermoforming.

Thermoforming is a process in which the extruded PSF sheet is reheated, then pressed between the two halves of a metal mold to form the desired end product such as fast food containers. After thermoforming, the molded shape is trimmed, sometimes printed, and packaged. Resulting scraps are ground and sent to scrap storage silos. This scrap is introduced into the primary extruder with virgin polystyrene. Polystyrene scrap typically makes up 35 percent of the total polystyrene fed to the primary extruder.



Potential VOC Recovery Points

- A Outside and Inside Extruded Bubble
- B Repelletizer Extruder Vent
- C Exhaust from Pneumatic Transfer of Reground Scrap Foam to Silos

Note:

[1] Capture system is not existing. Need to be developed.

Figure 4-1. Flow Diagram of a Typical Polystyrene Foam Sheet Manufacturing Process

4.3 EXTRUDED POLYSTYRENE FOAM BOARD

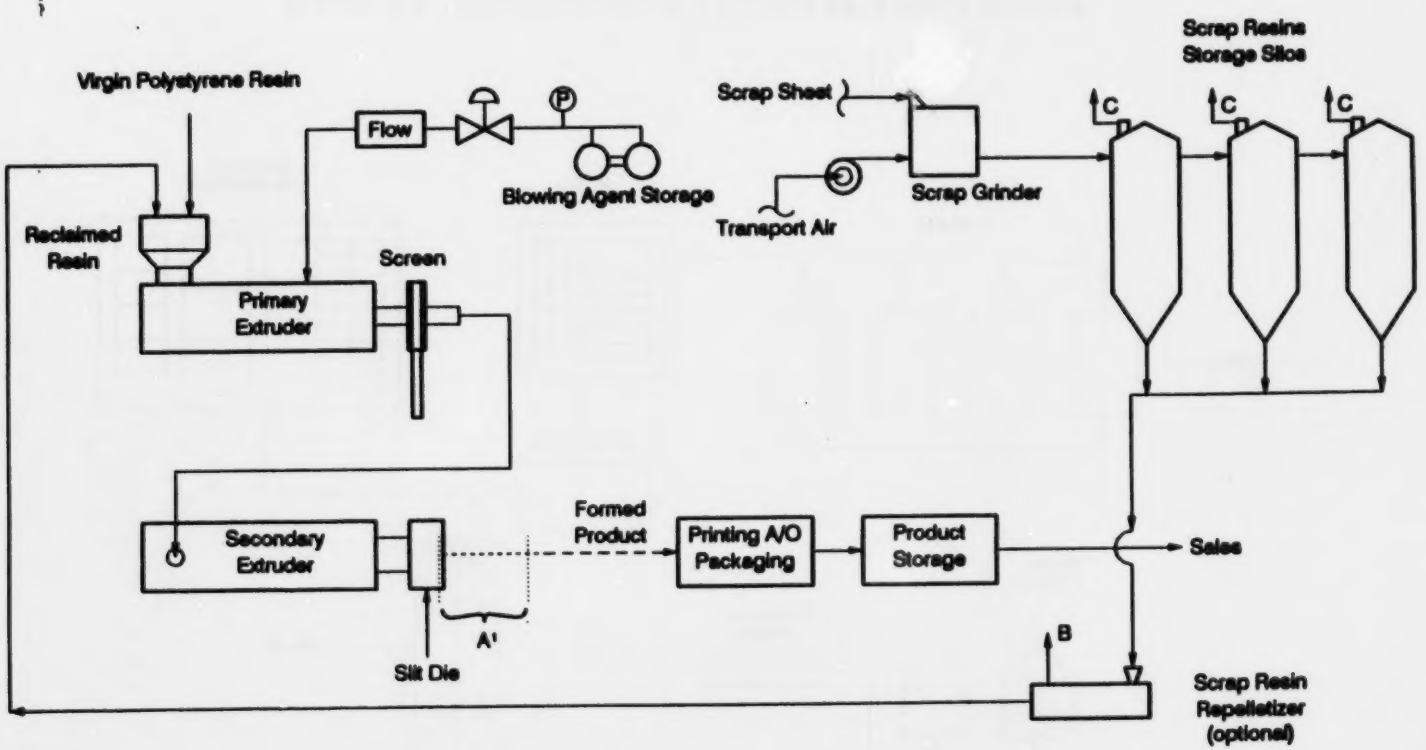
Polystyrene foam board ranges from 1.25 to 15 cm thick, with densities of 21 to 66 kg/m^3 (1.3 to 4 lbs/ft^3). The extrusion of PS foam boards is identical to that of PS foam sheets, with the exception that a simple slit aperture die is used instead of an annular die so that board is extruded as slabs rather than a tube. Following cooling of the PS board, it is trimmed to size and packaged. A typical PSF board manufacturing process flow diagram is shown in Figure 4-2. Some board is laminated with facing materials that act as a vapor barrier or aid in the retention of low conductivity gas.[4]

4.4 EXPANDABLE POLYSTYRENE (EPS)

Expandable polystyrene is produced from spherical polystyrene beads which have been impregnated with a volatile hydrocarbon such as pentane. The polystyrene beads are produced by polymerizing styrene in a water suspension and adding a volatile liquid such as pentane as a blowing agent. The beads typically contain five to seven percent by weight of the blowing agent. Prior to use the beads are stored at ambient temperatures in cartons with vapor barrier plastic liners to inhibit premature diffusion of the blowing agent from the beads.[5]

A typical EPS bead manufacturing process flow diagram is shown in Figure 4-3. Normally, the beads are expanded in one step and molded in another. Expansion is promoted by exposing the beads to a continuous flow of steam or hot air at temperatures of 212°F to 220°F within a process unit called a pre-expander. Batch and continuous processes are common. A typical EPS batch pre-expander process is shown in Figure 4-4. The transfer of heat vaporizes the volatile hydrocarbon trapped in the polystyrene matrix; the volatiles are released from the matrix causing the beads to foam and expand. This is the stage where the density of the raw beads is brought to approximately the density required for molding. The amount of expansion is controlled by steam pressure and temperature, and the bead feed rate.[6] This process is generally performed in a continuous mode.

Following the expansion process, the excess moisture acquired during steaming is eliminated with hot air, and the beads are transported to storage silos constructed of large mesh bags, where they are allowed to cool.[7] The beads are allowed to age for 4 to 24 hours, during which time a



Potential CFC Recovery Points

- A Outside and Inside Extruded Bubble
- B Repelletizer Extruder Vent
- C Exhaust from Pneumatic Transfer of Reground Scrap Foam to Silos

Note:

' CFC capture system is not existing. Need to be developed.

Figure 4-2. Flow Diagram of a Typical Polystyrene Foam Board Manufacturing Process

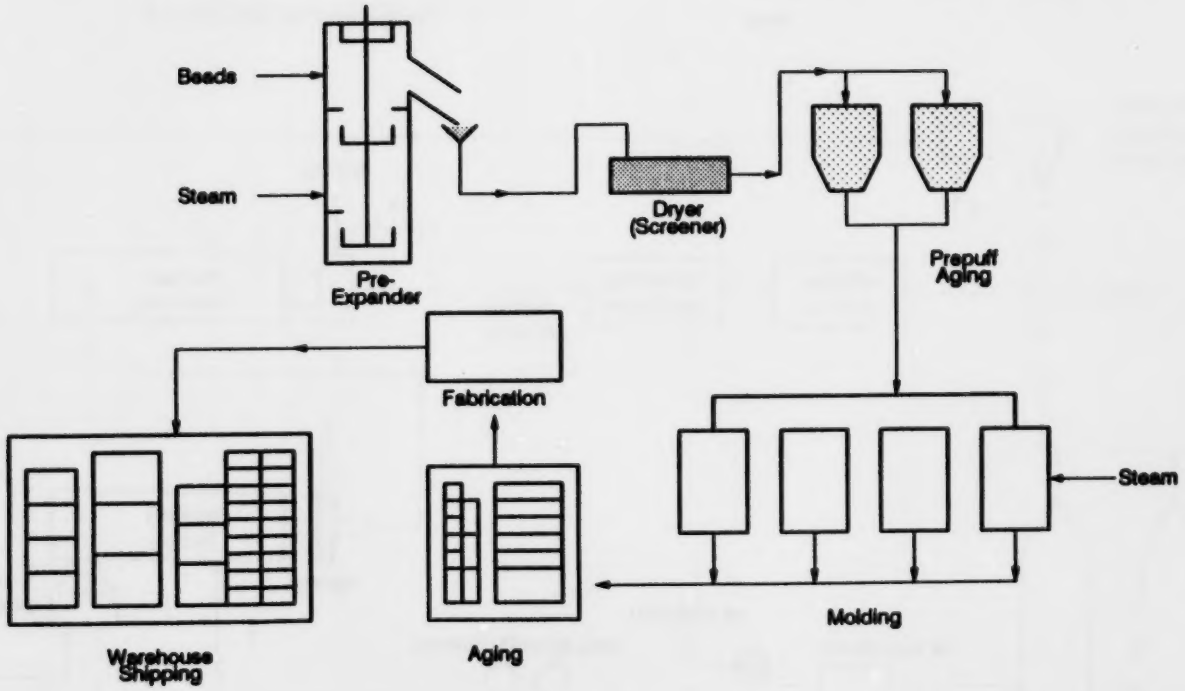


Figure 4-3. Flow Diagram of a Typical EPS Bead Process

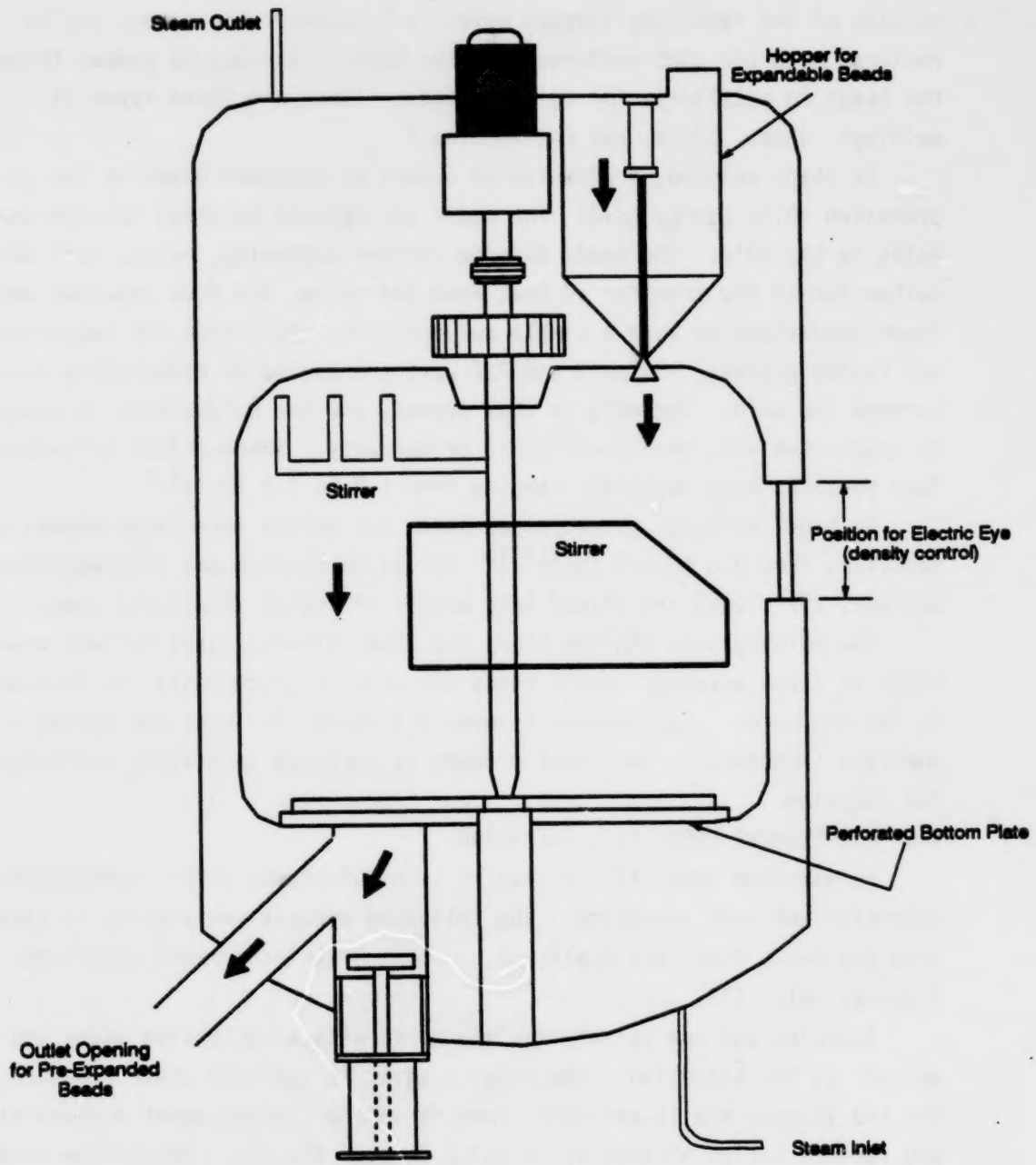


Figure 4-4. EPS Batch Pre-expander

portion of the remaining trapped volatile compounds evaporates, and is replaced with air that diffuses into the beads. Air may be pumped through the beads to accelerate the aging process. There are three types of molding: shape, block, and cup molding.[8]

In shape molding, a premeasured amount of expanded beads is fed to a preheated split cavity mold. The beads are exposed to steam through small holes in the mold. The beads undergo further expansion, become soft and molten due to the transfer of heat from the steam, and fuse together under these conditions to form a single polymer mass. Following the expansion and fusing process, the mold and PSF part are cooled by circulating water through the mold. The mold is then opened, and the molded part is ejected by compressed air, mechanical pins, or manually. Shape-molded polystyrene foam products have densities ranging from 1.0 to 2.5 lb/ft^3.[9]

In block molding, pre-expanded beads are molded into large blocks of densities from 0.8 to 1.0 lb/ft^3.[10] Following cooling and intermediate storage, the blocks are sliced into sheets or custom fabricated shapes.

Cup molding uses smaller beads and lower blowing agent content than block or shape molding. Small beads are used to accommodate the thin walls of the cup molds. Cup density is over 3.5 lb/ft^3.[11] Cups are molded at a moderate temperature; the final product is packaged in plastic and boxed for shipping.

4.5 POLYSTYRENE LOOSE FILL PACKAGING

Polystyrene loose fill packaging is manufactured with a combination of extrusion and bead expansion. The following process description is taken from the South Coast Air Quality Management District's Staff Report for Proposed Rule 1175.

Recycled and new polystyrene are mixed with a nucleating agent and melted, as for extrusion. The blowing agent is injected under pressure, and the viscous mix is extruded, foaming as the blowing agent evaporates, and forming hollow strands as it exits through the die. The hollow strands are cut into 3/4-inch pieces. The strands are then steamed for further expansion, as are EPS beads. Intermediate aging follows, and then the strands are further steam expanded, dried in ovens, and aged. The density of loose fill is about 0.2 lb/ft^3.[12]

REFERENCES

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2. See reference 1.

3. See reference 1.

4. See reference 3, Section 3.

5. Personal Communication with R. B. Coughanour, Private Consultant. Reviewer Comments on Draft Report, May 15, 1990.

6. See reference 4, Section 3.

7. Wiman, J. V. "Expandable Polystyrene Molding." Modern Plastics Encyclopedia, 1981-1982. McGraw-Hill, Inc., New York, New York, 1981. p. 296.

8. Tsitsopoulos, L. and M. Mills. Staff Report, Proposed Rule 1175: Control of Emissions from the Manufacture of Polymeric Cellular Products (Foam). South Coast Air Quality Management District, Rule Development Division. September, 1989.

9. See reference 8.

10. See reference 8.

11. See reference 8.

12. See reference 8.

5.0 PROCESS EMISSIONS

5.1 PROCESS EMISSIONS OVERVIEW

For processes using hydrocarbon blowing agents, VOC emissions are known to occur at various phases of PSF manufacture and use. There are three general classes of emissions: manufacturing emissions, prompt foam cell loss, and banked emissions. Manufacturing emissions are the loss of blowing agent during processes prior to storage of the final product. Emissions from extrusion, thermoforming, and scrap grinding during PSF sheet manufacturing, and pre-expanding and molding emissions during EPS manufacturing are examples of manufacturing emissions. Prompt foam cell losses occur in the first one to two months following manufacture, either during storage and shipping, or consumer use. Banked emissions are associated with PSF boardstock production and, therefore, are limited primarily to CFC-12 emissions. Banked emissions result when a portion of the blowing agent sealed in the closed cell structure of the boardstock slowly diffuses out of the foam over a long period of time. Generally, this occurs during consumer use of the product. The half-life of CFC-12 in PSF board, for instance, is estimated to be anywhere from 40 to 200 years.

In addition to the three general classes of emissions discussed above, manufacturing losses can be further classified as fugitive or point source emissions. Point source emissions originate from a single location such as a process vent or exhaust stack. Fugitive emissions originate from larger, more general areas such as storage warehouses.

The manufacturing processes described in Section 4.0 afford different opportunities for blowing agents to escape. Industry-generated data exist on points of emissions during manufacturing and the percentage of blowing agent lost at each of these points. Characterization of VOC emissions from the EPS bead process was developed from an industry study based on emission measurements from 20 to 25 plants.[1] The emissions profile for the

extrusion process is based on blowing agent emissions data from several producers, and on dialogue with representatives from major extrusion companies.

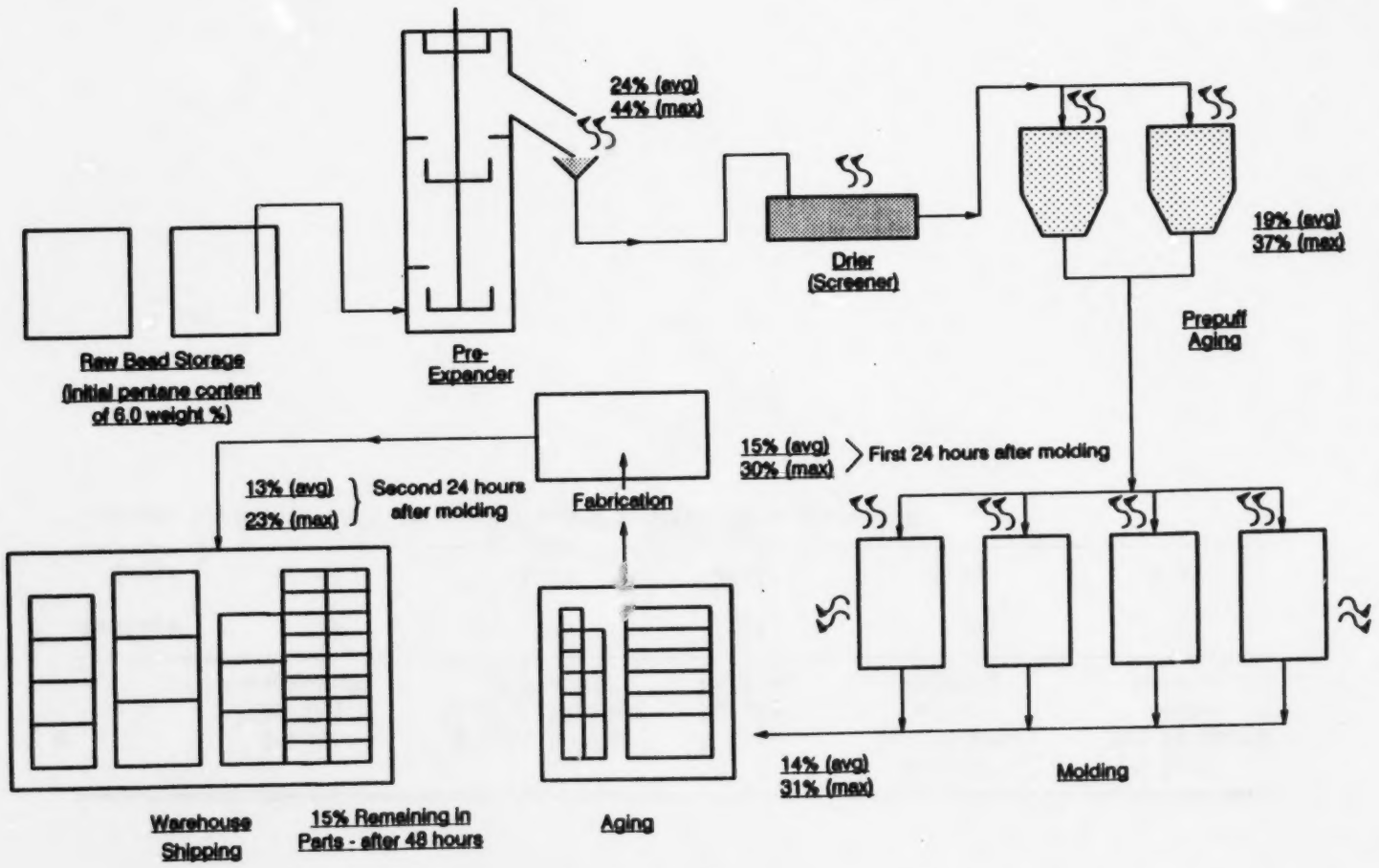
5.2 EMISSIONS SOURCES

5.2.1 Expandable Beads

As described in Section 4.0, EPS beads are produced by injecting pentane into polystyrene resin. The beads are expanded, and molded or cut in a separate process, usually at a different facility.

Manufacturing emissions of VOC occur primarily during expanding (blowing) and molding. Pentane emissions are also known to occur during bead impregnation.[2] In some cases, bead impregnation occurs during the styrene polymerization process. These particular emissions are addressed by proposed Standards of Performance for New Stationary Sources: Propylene, Polyethylene, Polystyrene, and Poly(ethylene terephthalate) Manufacturing Industry [52 FR 36678, September 30, 1987].[3] However, a small number of companies inject pentane into polystyrene resin. Emissions that may occur during this process are not covered by the NSPS; this report addresses only those EPS emissions that occur as part of the expansion and molding processes. There are several points of emission during the expanding and molding process. Figure 5-1 shows points of manufacturing emissions and the percentage of total blowing agent (pentane) emitted at each point.

Total weight percent of pentane in raw beads is from 6 to 7.5 percent. This is the optimal concentration of blowing agent; less would prevent expansion to desired densities, and more would not significantly improve the product. Pentane concentrations can be lowered by using it in combination with other blowing agents, such as CO2. Alternative blowing agents and blowing agent combinations are discussed in Section 6.3. Pentane loss analysis figures from an industry study demonstrate that EPS bead pentane is lost primarily during expansion and molding. Additional significant losses occur during storage and shipping, and fall in the category of prompt foam cell losses (see Table 5-1). The end product will typically have an average pentane weight of less than two percent.



From: Caughanour, R.B. The Pentane Issue. Presented at 16th Annual SPI Expanded Polystyrene Division Conference; March 17, 1988; San Diego, California.

Figure 5-1. Average and Maximum Percent Pentane Losses at Manufacturing Emissions Points for EPS Facilities

TABLE 5-1. PENTANE LOSS ANALYSIS FOR EPS BEAD PRODUCTS[4]
(Percent of Original Pentane Blowing Agent)

	% Lost During Expansion	% Lost During 24 Hrs. Storage of Prepuff	% Lost During Molding	% Lost 1st 24 Hours after Molding	% Lost 2nd 24 Hours after Molding
Average	24	19	14	15	13
Range	10-44	5-37	4-31	5-30	3-23

Average % pentane left in molded product after 48 hours = 15%.

5.2.2 Extruded PSF Boardstock

Extruded PSF board depends, to some extent, upon its blowing agent content for its insulating properties. Extruded board is blown primarily with CFC blowing agents. Only about 15 percent of the blowing agent is emitted during the manufacturing process.[5] Emissions occur primarily as the foam leaves the extruders. The remainder is emitted gradually over several years as banked emissions.[6] As blowing agent is lost and replaced by air, the board loses some insulating value; however, even when all blowing agent is replaced by air, PSF board is still an effective insulation.

To a large degree, the thickness of the board determines the rate of emissions; the thicker the board, the slower the emissions rate. Because the percent blowing agent lost during manufacture is substantially lower for extruded board than for extruded sheet or EPS products(15 percent versus 50 to 80 percent), and because the blowing agent used in extruded board is usually CFCs, emissions from extruded board are not significant relative to sheet and EPS emissions. Therefore, the extruded board process will not be considered further in this report. If, due to regulatory action, the extruded board industry moves towards hydrocarbon blowing agents, emissions from this process will need to be reexamined.

5.2.3 Extruded PSF Sheet

The PSF sheet manufacturing process is similar to the board process; however, more of the blowing agent is emitted during processing. Table 5-2 shows the approximate percentage losses of blowing agent during manufacturing, storage, and use. Approximately 50 percent of the blowing agent is emitted during manufacture. Emissions will vary depending upon the diffusion rate of the particular blowing agent being used, as well as the product being thermoformed. Different product sizes and shapes require different mold configurations; the amount of scrap sheet generated during thermoforming varies according to the mold configuration. Since significant emission control can be achieved during the scrap reclaim process, the amount of scrap generated (and, hence, the product type) ultimately effects the blowing agent emissions. The most significant manufacturing emissions occur during scrap grinding and re-extrusion of

TABLE 5-2. SUMMARY OF VOC EMISSION SOURCES AND EXAMPLE DISTRIBUTION IN POLYSTYRENE EXTRUSION PRODUCTS[11]

Emission Source	Percent[a] From Extruded Sheet	Percent[a] From Extruded Boardstock
Manufacturing Losses		
Extrusion	10	10
Intermediate Storage	5	5
Thermoforming	5	---
Scrap Grinding/re-extrusion	30	---
Prompt Foam Cell Losses (within 1-2 months)	50	1
Banked Emissions	0	84
	100.0	100.0

[a]These estimates may vary among producers based on blowing agent content and process conditions.

recycled sheet. Minor losses occur during extrusion and thermoforming as the foam is heated. Prompt foam cell losses are also significant; about 50 percent of the blowing agent is lost within two months after manufacture. There are virtually no banked emissions in PSF sheet.[7, 8, 9, 10]

5.3 VOC EMISSION RATES

This section presents estimates of VOC emission rates and concentrations for "typical" EPS and sheet manufacturing plants. These estimates are based on the assumptions noted on Tables 5-3 and 5-4. They are not based on actual emissions measurements. Total VOC emissions at any particular manufacturing facility will vary significantly based on the facility size, process, and type of foam products produced. However, the emission estimates presented here can provide some guidelines on emissions as a function of plant production. Calculations of emissions estimates are shown in Appendix B.

5.3.1 Model Plants

Tables 5-3 and 5-4 present production and material usage characteristics for small, medium, and large plants producing PSF sheet and EPS bead products, respectively. The emission rates were calculated assuming a 50 weeks per year, 7 days per week, and 24 hours per day production schedule. The annual production volumes, figures, and emission rates are based on the references and additional assumptions given in each table.

5.3.2 PSF Sheet

The total manufacturing emissions losses from the model sheet plants consist exclusively of pentane, which is assumed to comprise 4.8 weight percent of the product. Manufacturing losses are assumed to be 50 percent of the total VOC content. Pentane losses for small, medium, and large facilities are calculated to be 24, 95, and 252 tons per year, respectively. The overall production pentane loss is 45 pounds of pentane per ton of polystyrene foam production. The total plant production exhaust flow ranges from 3805 to 31,395 scfm to maintain an exhaust VOC concentration at 200 ppmv.

5.3.3 EPS Beads

The total manufacturing emission losses from the model EPS bead plants consist exclusively of pentane, which is assumed to comprise six weight percent of the product. Manufacturing losses are assumed to be 60 percent

TABLE 5-3. MODEL PLANTS - PSF SHEET

Plant Size	Small	Medium	Large
Annual Production, tons/yr	1,000[a]	5,000[b]	10,500[b]
Production Emissions, lb/yr (tpy)[c]			
Pentane	48,000 (24)	190,000 (95)	504,000 (252)
Total Plant Production Exhaust Flow (scfm)[d]	3805	15,400	32,400

[a]Based on assumption that small facility represents 20 percent the capacity of a medium-size facility.
[b]Annual production rates based on model facility in Reference 4 (Section 3) and Reference 9.
[c]Assumes use of pentane at 4.8 wt. percent of product, and 50 percent loss during manufacturing (Reference 6.1). Does not include prompt foam cell losses.
[d]Standard cubic feet per minute. Based on a waste stream concentration of 200 ppm.

TABLE 5-4. MODEL PLANTS - EPS BEAD PRODUCTS

Plant Size	Small	Medium	Large
Annual Production, tons/yr[a]	1,500	3,000	4,500
Production Emissions, lb/yr (tpy)[b]			
Pentane	110,000 (55)	216,000 (108)	326,999 (163)
Total Plant Production Exhaust Flow (scfm)[c]	3,570	7,020	10,600

[a]Based on range of annual production rates given for model facilities in Reference 4 (Section 3).
[b]Assumes use of pentane at 6 wt. percent of beads, and 60 percent loss during manufacturing (Reference 1). Actual losses may range between 50 and 85 percent (Reference 11). Does not include storage losses.
[c]Standard cubic feet per minute. Based on a waste stream concentration of 200 ppm.

of the total VOC content. Pentane losses for small, medium, and large facilities are calculated to be 55, 108, and 163 tons per year, respectively. The overall production loss is 72 pounds of pentane per ton of production. The total plant production exhaust flow ranges from 3750 to 10,598 scfm to maintain an exhaust pentane concentration of 200 ppmv.

5.3.5 Summary

Based on the emission rates calculated for each of the model facilities, the EPS bead facilities produce the largest amount of VOC emissions (72 pounds VOC/ton of production), while extruded sheet manufacturing VOC losses are approximately 45 pounds per ton of production. Losses are based on the assumptions noted in Tables 5-3 and 5-4.. Actual percent losses will vary depending on processing and product characteristics.

In addition to manufacturing losses modeled here, PSF sheet and EPS bead products continue to lose blowing agent after processing. Industry testing has indicated that some of these losses, particularly in bead products, occur in the first 24 to 48 hours following manufacturing, while other products retain some blowing agent for up to two months.[12,13] Based on the emission losses calculated from the model facilities, losses from the model PSF sheet facilities are approximately 62 percent as great as the losses from the EPS bead model facilities.

5.4 NATIONAL VOC EMISSION ESTIMATES

Most of the previous research on emissions from polystyrene foam blowing has focused on chlorofluorocarbon emissions. Since the Montreal Protocol (40 CFR Part 82) was passed in August 1988 restricting the production and consumption of a number of fully halogenated CFCs, the polystyrene foam industry has focused most of its research efforts on developing alternative blowing agents. These alternatives include, but are not limited to, HCFC-22, HFC-134a, HCFC-142b, hydrocarbons, and blends of these chemicals together, and with carbon dioxide.

The industry is currently in a state of transition concerning which compounds to use as blowing agents, and different segments of the industry are moving in different directions. In this report, estimates of national VOC emissions from the use of hydrocarbons as blowing agents were calculated based on production data from the literature and from the industry trade associations. The estimates of national VOC emissions presented in Table 5-5 are based on blowing agent usage patterns reported

TABLE 5-5. ESTIMATED NATIONAL VOC EMISSIONS FROM PSF FACILITIES

Process	% of Industry Using HC for Blowing Agent	Total 1988 Production[a] (lbs/yr)	Amount HC Used for Blowing[b] (lbs blowing agent/ lbs product)	Amount Blowing Agent Lost During Processing[c]	Emissions (tons/yr)
EPS Foam Beads	100%[d]	5.58×10^8	0.06	85%	14,230
PS Foam Sheet	65%[b]	6.5×10^8	0.048	50%	5,062
				TOTAL:	19,292

[a]Source: Journal of Modern Plastics, 1989.
[b]Source: "Control Technology Overview Report: CFC Emissions from Rigid Manufacturing." Prepared by Radian Corporation for the U.S. EPA, September 1987.
[c]Emissions from EPS foam beads and PS foam sheet include manufacturing emissions and short-term storage emissions.
[d]Source: Modern Plastics, October 1987.

for the industry during 1987 and 1988. Calculations of estimates are included in Appendix B. A discussion of alternate blowing agents and their current status is included in Section 6.0 of this report.

5.4.1 EPS Beads

Based on review of the literature and contacts with industry, it appears that hydrocarbons are used exclusively as the foam blowing agent for producing foam beads.[14] It is estimated that approximately six pounds of blowing agent are used per 100 pounds of foam beads produced.[15] Eighty-five percent of the hydrocarbon blowing agent is emitted during processing and storage, resulting in estimated annual VOC emissions of approximately 14,200 tons.

5.4.2 PS Foam Sheet

Manufacturers of foam sheet are currently moving away from the use of CFC-12 as a blowing agent. Recent estimates indicate that 60 to 70 percent of the foam sheet that is produced is blown with hydrocarbons, primarily pentane.[16] Combinations of CO_2 and pentane are also being used successfully. (See Section 6.3 for further discussion.) Approximately 50 percent of the blowing agent is emitted during processing, and the remaining 50 percent is lost during storage or over the first one to two months of product life. National manufacturing losses of hydrocarbons from foam blowing of PS sheet are estimated at 5062 tons per year. Delayed losses occurring during storage, shipment, and use are also estimated at 5062 tons per year.

5.5 STATE REGULATIONS

Regulation of PSF manufacturing varies from state to state. Many have regulations and permitting programs addressing VOC emissions in general; existing regulations pertaining specifically to PSF manufacturing are described below.

5.5.1 South Coast Air Quality Management District

The South Coast Air Quality Management District (SCAQMD) of California has adopted Rule 1175 [Control of Emissions From the Manufacture of Polymeric Cellular Products (Foam)]. The rule limits VOC, CFC, and methylene chloride emissions from EPS, PSF extrusion, polyurethane, and other polymer foam facilities. Rule 1175 requires the control of manufacturing emissions, and does not differentiate between fugitive and

non-fugitive emissions. For EPS bead, the total uncontrolled emissions, including the residual blowing agent in the manufactured product, must not exceed 2.4 pounds/100 pounds of raw material processed. This would mean, for example, for a product with six percent blowing agent, at least 60 percent of the blowing agent must be controlled during processing and storage. Extrusion facilities must reduce emissions by 40 percent in 1991 and 100 percent in 1994 (over 1988 baseline emissions). If compliance is not demonstrated in due time, capture and control devices must be installed to achieve at least 90 percent and 95 percent efficiency, respectively. Compliance with the SCAQMD rule may be achieved by using alternative blowing agents that are exempt from the rule, such as HCFC-22, HCFC-123, HFC-134a, and HCFC-142b.

As discussed in previous sections, some emissions occur from the final products after the manufacturing process. These emissions are higher during the first few days following manufacturing than at other times. If total emissions exceed the above-cited cutoffs or if the final product, 15 minutes after manufacture, contains more than 1.8 percent blowing agent, Rule 1175 requires the storage of the foam products and capture of vented emissions in order to reduce the post manufacturing losses. The final product must be stored for 48 hours (24 hours if processing less than 800,000 pounds per year). EPS facilities processing less than 200 pounds per day are exempt from the total regulation.

5.5.2 Kern County, California

Polystyrene foam manufacturing has been regulated in Kern County, California since December 1988 under Rule 414.4. Rule 414.4 bans the use of any VOC, CFC-11, or CFC-12 as a blowing agent if no emission collection/control systems are operated. Alternatively, a facility may install a collection system on controllable VOC emission sources; controllable sources are defined as fluff silos or bins, reclaim extruders, and reclaim die hood exhausts. Collection systems must meet the requirements of the American Conference of Governmental Industrial Hygienists, and the Sheet Metal and Air Conditioning Contractors National Association Guidelines, and must be vented to a combustion device achieving at least 95 weight percent control efficiency. Additionally, Rule 414.4 requires any VOC blowing agent storage tank with greater than 200 gallons

capacity to be equipped with a collection and control device or to be sufficiently pressurized to prevent the release of VOC emissions.

5.5.3 Illinois

The Illinois State regulation controls sources processing plastic foam scrap or "fluff" from the manufacture of foam containers and packaging material to form resin pellets, if uncontrolled VOC emissions exceed 100 tons per year. These sources must operate in compliance with RACT, which requires an emission capture and control system achieving at least an 81 percent reduction in uncontrolled VOC emissions. Emissions from the extrusion process are not regulated.

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3. Telecon. McLean, J., Radian Corporation with Roy, S., U.S. EPA, OAQPS, March 21, 1990. Conversation regarding bead impregnation emissions.

4. See reference 1.

5. See reference 6, Section 3.

6. See reference 6, Section 3.

7. Letter from Charles Krutchen, Mobil Corporation, to Susan R. Wyatt, U. S. Environmental Protection Agency, May 9, 1990.

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9. Letter from Val W. Fisher, Amoco Foam Products Company, to Susan R. Wyatt, U. S. Environmental Protection Agency, May 7, 1990.

10. Telecon. McLean, J., Radian Corporation, with Cooper, D., Dow Chemical Corporation, June 6, 1990. Conversation regarding PSF sheet extrusion.

11. See reference 7

12. See reference 1.

13. Telecon. McLean, J., Radian Corporation with Krutchen, C., Mobil Chemical Company, July 6, 1990. Conversation regarding banked emissions.

14. See reference 12, Section 3.

15. See reference 8, Section 3.

16. See reference 8, Section 3.

6.0 EMISSION CONTROL TECHNIQUES

This chapter discusses VOC emission capture and control techniques which have been applied to the PSF industry. The demonstrated controls discussed include incineration and carbon adsorption; some potential non-demonstrated control techniques are also discussed briefly.

Overall efficiency and costs of VOC control depend largely upon characteristics of the emission points involved, and the efficiencies of capture and control devices. The cost of air pollution control devices increases as the flow rate of air requiring treatment increases, primarily because higher flow rates require larger control devices. It follows that low flow, high concentration streams are desirable for achieving reasonable cost effectiveness. Low flow and high concentration are achieved through good capture device efficiency and design.[1] In addition, as discussed in Section 5, "Process Emissions", VOC concentrations should be maintained in the capture and delivery systems at or below 25 percent of the lower explosive limit (LEL) (3500 ppm for pentane), due to safety considerations. A related concern is worker exposure to VOC emissions. Capture device design as well as work area ventilation systems effect ambient VOC levels, which must be maintained below the threshold limit value (TLV) (600 ppm for pentane). Ideally, a capture system would optimize collection efficiency, waste stream concentration, and flow rate to maintain safety standards and minimize costs.

6.1 CAPTURE SYSTEMS

There are three general classes of capture devices: local, general, and complete enclosure.[2] Each type can achieve ranges of collection efficiencies and flow rates depending on factors such as the number and types of emission sources to which each device is applied, the proximity to the emission source, and the amount of worker traffic in the area. Capture efficiencies are difficult to measure, and can be very site specific.[3]

6.1.1 Local and General Capture Devices

Local capture devices consist of hoods or intake ports located near a single source to collect emissions. The collection efficiency and exhaust flow rate for local capture devices are affected by air turbulence in the immediate vicinity, the design capture velocity, and the amount of air inflow, or dilution, to the emissions stream.[4] General capture devices collect emissions from more than a single source. A single vacuum hood collecting emissions from several extruders is an example of a general device.

6.1.2 Total Enclosure Capture Devices

It may be possible to enclose limited areas of a process completely, and vent all the area emissions to a control device. Capture efficiency for complete enclosure can be close to 100 percent.[5] Enclosure might be possible for areas where personnel traffic is at a minimum. Areas where automated equipment such as extruders, scrap grinders, or thermoformers are located would be suited to total enclosure capture devices. It may be possible to apply total enclosure devices to storage areas. Partial enclosures, such as customized or extended hoods, are feasible in more situations than total enclosure, and can be expected to achieve greater capture efficiencies than local or general devices, though not as great as total enclosure.

6.1.3 Cascading of Capture Devices

Cascading is a concept in which VOC collection devices are arranged in a series such that VOC is moved from an area of lower capture efficiency to an area of higher capture efficiency. The benefit of cascading is that the same mass of air is used to collect VOC from more than one area, resulting in an increased VOC concentration. This results in an overall increase in VOC capture efficiency, and consequently, VOC control efficiency. Cascading may also reduce the amount of air required to capture VOC emissions, and thus the size, capital cost, and annual operating cost, of pollution control equipment.

It is important that the air be moved from an area of lower collection efficiency to an area of equal or higher collection efficiency. Thus, air collected by a general or local collection device could be used as make-up air for a completely closed area. One example of this concept would be the use of air collected by a general collection device in a thermoforming area

as the air supply for a pneumatic conveyer system transporting PSF scrap to storage silos.

6.1.4 Current Industry Practice

Because most PSF facilities are only now being considered for regulation, there are no well established conventions for VOC capture. State environmental agencies indicate that both local and total enclosure capture devices have been used in the EPS industry.[6] Other facilities plan to use room-type enclosures for control of VOC emissions from pre-expansion operations and/or molding operations. The room enclosures will be ventilated to maintain the TLV of 600 ppm; exhaust will be vented to control devices. Local capture devices can also be used to deliver emissions to existing boilers.[7] Hoods can be attached directly to the pre-expanders and fluidized bed driers, and vented to control devices.

Data on the capture efficiencies of these various systems are not available, primarily because of the difficulty of measurement. Generally speaking, engineering estimates put capture efficiencies for devices other than total enclosure at approximately 75 percent under optimal conditions, while efficiencies as low as 30 percent have been measured.[8] Operators of the facilities with total enclosure estimate capture efficiencies at close to 100 percent; however, no data are available to verify this estimate.[9] The SCAQMD's Amended Rule 1175 (see Section 5.0) requires a capture efficiency of 95 percent for VOC emissions. Some industry contacts feel that total enclosure of the most significant emission points (i.e., pre-expanders, molders, and extruders) is necessary in order to achieve 95 percent capture efficiency.[10]

6.2 ADD-ON CONTROLS

Add-on control devices may be divided into three general groups: incineration, adsorption systems, and alternate technologies. Of the add-on control technologies evaluated in this report, incineration and carbon adsorption are the only demonstrated and readily available technologies for controlling VOC emissions from polystyrene foam blowing facilities. Information on the possible alternate technologies is provided with a discussion of the potential advantages and disadvantages. Cost effectiveness figures for carbon adsorption and thermal incineration controls are estimated in Section 7.0. Control of emissions through the use of alternate blowing agents is discussed in Section 6.6.3.

6.2.1 Incineration

The use of incineration has been demonstrated for controlling VOC emissions from polystyrene foam manufacturing facilities. Several States have issued permits allowing incineration of VOC emissions at EPS facilities[11,12], and industry contacts report incineration for VOC control.[13,14] Recently, an EPS facility has been issued a permit by the SCAQMD to install cogeneration boilers, but has not initiated construction or installation.

Two types of incinerators are available, thermal and catalytic. Thermal incineration involves the oxidation of organic vapors to carbon dioxide and water. The exhaust stream is incinerated in a combustion chamber at temperatures in the range of approximately 1600°F (870°C). Catalytic incinerators use a catalyst bed to oxidize the organic vapors and operate at lower temperatures of 750° to 1000°F (400° to 540°C). Important incineration design factors are residence time, gas stream flow rate, operating temperature, and waste gas heat content.

The heat content of an exhaust stream is important in determining auxiliary fuel and air requirements. Exhaust streams with heat contents of 20 to 50 Btu/scf, corresponding to 40 to 100 percent of the LEL, must be diluted with excess air or auxiliary fuel to meet insurance companies' safety regulations for flammable gases.[15] Streams with 13 to 20 Btu/scf correspond to 25 to 40 percent of the LEL. For example, a VOC stream containing 3500 ppmv of pentane (25 percent of LEL) has a heating value of approximately 13 Btu/scf.

Pollutant streams with heat contents less than 50 Btu/scf require auxiliary fuel to maintain combustion temperatures.[16] Although pollutant streams with heat contents ranging from 50 to 100 Btu/scf have sufficient heat content to support combustion, auxiliary fuel may be needed for flame stability. When the heat content of a VOC stream is greater than 100 Btu/scf, the stream possesses sufficient heat content to support combustion alone and may even be considered for use as a fuel gas or boiler feed gas.

Thermal incinerators used to control VOC emissions at PSF facilities will generally require supplemental fuel. Heat recovery equipment is nearly always used with incinerators applied to low VOC concentration streams to reduce the amount of supplemental fuel required. The amount of heat recovery achievable can be up to 95 percent.[17] Heat recovery can be

accomplished using a non-contact heat exchanger system. An example of a non-contact heat recovery device is a tube and shell heat exchanger. This type of heat exchanger consists of a bundle of parallel tubes inside a cylindrical shell. The hot incinerator flue gases flow through the heat exchanger on the shell side. The vapor stream to be incinerated flows through the heat exchanger on the tube side and absorbs heat from the hot flue gases through the walls of the tubing, thereby increasing its heat content and reducing the need for auxiliary fuel. Generally, the more energy efficient incinerators have lower operating costs due to the reduced fuel consumption, but a higher initial capital cost resulting from the addition of heat exchange equipment.

Regenerative thermal incineration is currently used to control VOC emissions at several major PSF facilities. These systems use direct heat exchangers constructed of ceramic materials that can tolerate the high temperatures needed to achieve ignition of the waste stream. The ignited gases react in the combustion chamber and subsequently pass through another ceramic bed, heating it to the combustion chamber outlet temperature. The flow is periodically reversed to continually feed the inlet stream to the hot bed.[18] Energy recovery efficiency can be as high as 95 percent; associate capital costs are high, but generally are offset by a decreased need for auxiliary fuels.[19]

For the expected range of VOC concentration levels encountered in PSF manufacturing (600-3500 ppmv), thermal incinerators can achieve 99 percent or greater VOC destruction, while catalytic incinerators are capable of achieving up to 95 percent VOC destruction.[20]

Some EPS manufacturing facilities have existing boilers in place to provide steam in the pre-expansion and molding steps. VOC emissions could possibly be vented to existing boilers for incineration. The benefit of using existing boilers for emissions control is a reduction in capital and operating costs. The only capital investments involved are the capture systems ductwork, and fans and boiler modifications required to direct emissions to the boiler. Where applicable, use of existing boilers would be the most effective control option (see Section 7.3).

In general, however, existing boilers are designed for steam production, not for VOC control. Emission capture devices must be designed based upon these existing boiler operating parameters, such as fuel firing rates, temperature, and pressure. When a new boiler or other incineration

device is to be purchased, the operating and design parameters can be calculated to fit facility needs and a suitable device can be constructed. The design effort is considerably more labor intensive when capture devices must be designed to meet the existing design and operating parameters of existing boilers.[21] Existing boilers may not be able to control all the emissions from a facility, and an additional incineration device may be required. The capital costs associated with the use of existing boilers for control devices are discussed in Section 7.0, "Control Costs". The incineration of chlorinated compounds can produce combustion products such as hydrochloric and hydrofluoric acids, and may require the use of corrosion-resistant materials and tail gas scrubbers. This would significantly increase the projected control costs.

6.2.2 Adsorption

Adsorption is a mass-transfer operation involving interaction between gaseous and solid phase components. The gas phase (adsorbate) is captured on the solid phase (adsorbent) surface by physical or chemical adsorption mechanisms. Physical adsorption occurs when intermolecular van der Waals forces attract and hold the gas molecules to the solid surface. Chemisorption occurs when a chemical bond forms between the gas and solid phase molecules. A physically adsorbed molecule can readily be removed from the adsorbent under suitable temperature and pressure conditions, while the removal of a chemisorbed component is much more difficult.

The most commonly used industrial adsorption systems are based on the use of activated carbon as the adsorbent. Carbon adsorption devices have been designed and installed for the successful control of VOC emissions in PSF facilities.[22] Activated carbon is effective in capturing certain organic vapors, including pentane, by the physical adsorption mechanism. In addition, the adsorbate may be vaporized for recovery by steam regeneration of the carbon bed.

The design of a carbon adsorption system depends on the chemical characteristics of the VOC being recovered, the physical properties of the inlet stream (temperature, pressure, and volumetric flow rate), and the physical properties of the adsorbent. The mass flow of VOC from the gas phase to the surface of the adsorbent, or rate of capture, is directly proportional to the difference between the VOC concentration in the gas phase and the adsorption potential of the solid surface. In addition, capture rate is dependent on the adsorbent bed volume, the surface area of

adsorbent available to capture VOC, and the rate of diffusion of VOC through the gas film at the gas and solid phase interface. Physical adsorption is an exothermic operation that is most efficient within a relatively narrow range of temperature and pressure. A schematic diagram of a typical fixed bed, regenerative carbon adsorption system is shown in Figure 6-1.

Vapors entering the adsorber stage of the system are passed through the porous activated carbon bed. Adsorption of the vapors occurs in the bed until the activated carbon is sufficiently saturated with VOC to result in VOC breakthrough. At this point, the VOC-laden air stream typically is routed to an alternate bed while the saturated bed is regenerated, usually with steam. Therefore, most carbon adsorption systems will consist of at least two carbon beds.

For the expected range of VOC concentration levels encountered in PSF manufacturing (600 to 3500 ppmv), carbon adsorption devices can achieve up to 99 percent removal efficiency.[23] Polymerization of styrene on the carbon is a concern because it would quickly deactivate the bed. However, the styrene content in vent streams from PSF facilities is expected to occur at trace levels. Additionally, carbon adsorption systems have been successfully operating at facilities where styrene concentrations are higher than those expected in PSF manufacturing. There has been no indication that styrene is polymerizing on the bed at these facilities. Another design consideration for those instances where a mixture of pentane and CFC is used is the difference in equilibrium adsorptive capacities of pentane and CFC compounds. At a partial pressure of 0.0002 psia, the equilibrium adsorptive capacity of virgin carbon for pentane is 12 pounds per 100 pounds of carbon, while the equilibrium adsorptive capacity of CFC-12 is only 7 pounds per 100 pounds of carbon, making the removal of CFC-12 the limiting design criteria.

6.2.3 Alternate Technologies

Three technologies have been identified that may serve as alternatives to carbon adsorption and incineration. The discussion of solvent scrubbers and refrigeration technologies is taken directly from SCAQMD's Staff Report on Proposed Rule 1175.[24] None of these technologies has been proven commercially in the PSF industry.

Solvent Scrubbers. In the scrubber, the pentane in emissions streams is absorbed by a counter-current flowing solvent. The

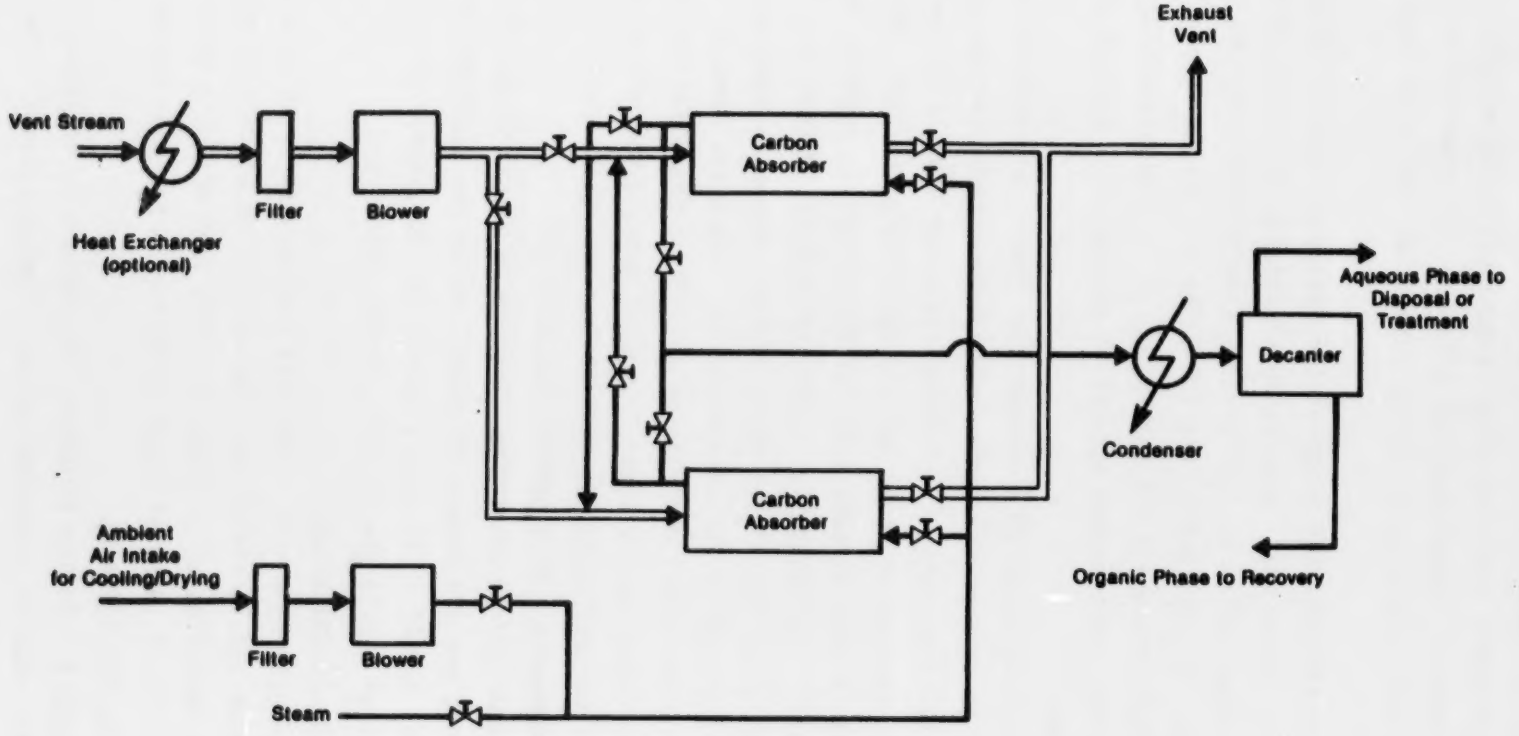

Figure 6-1. Carbon Adsorber System Process Flow Diagram

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pentane is stripped from the solvent and recovered. The solvent circulates back to the scrubber. Minimum size would be for 5000 cfm of air. Capital costs are relatively high. A large plant could have multiple small scrubbers with only one stripper and possibly save on large ductwork costs.

Refrigeration. The emissions stream containing pentane is refrigerated to condense the pentane. This approach is economically practical where relatively low air flow and high pentane concentrations are possible. As the concentration of pentane decreases, the amount of energy required to condense out the pentane increases (because lower temperatures are necessary). Since many of the contaminated air streams in the PSF industry have low concentrations, high operating costs will usually make a refrigeration control system impractical. However, there are selected instances where this technology would be appropriate.

Soil Biofiltration. Soil biofiltration is a promising alternative technology for removing VOCs such as propane, butane, pentane, and styrene from contaminated air streams. The contaminated air stream is passed through a soil bed, and the VOC is adsorbed to the soil colloids. Soil bacteria oxidize the VOCs aerobically, producing CO_2 and water. The bacteria regenerate themselves and the oxidation process renews the soil's adsorptive capacity. Approximately 10 square feet of land is required to treat each cfm of contaminated air.[25, 26]

Soil biofiltration test results have indicated that a VOC removal efficiency of greater than 90 percent is possible.[27] Biofiltration beds are known to be operating successfully in at least one commercial facility, where pentane and propane are being removed, and are currently being tested in several other facilities. Biofiltration offers several advantages over other pollution control alternatives, including:

- A low capital cost and minimal operating costs;
- No fuel or oxidants are required;
- No secondary pollutants are generated; and
- Bed operation is safe both for the environment and the workers.[28]

The major disadvantage to soil biofiltration is the large land area required for high VOC removal efficiency.

6.3 ALTERNATE BLOWING AGENTS

The PSF industry uses a variety of blowing agents including both hydrocarbons and chlorofluorocarbons. In PSF sheet production, the most commonly used hydrocarbon blowing agent is pentane and the most commonly used chlorofluorocarbons have been CFC-11 and CFC-12. Until recently, polystyrene boardstock products were blown almost exclusively with CFC-12 because it provides board with superior insulating quality. Expandable polystyrene beads are blown exclusively with hydrocarbons. Recent widespread concern over depletion of the earth's ozone layer due to CFC emissions and the eventual total phaseout of CFCs has prompted major producers of PSF sheet and board to reevaluate their commitment to the use of CFC. Additional concerns over air pollution caused by VOC emissions have caused similar evaluations regarding the use of such hydrocarbon blowing agents as pentane. The ideal alternative blowing agent would minimize the threat to the ozone layer and the quantity of VOC emissions, and have the chemical and physical properties required for each of the various end products. This is particularly important for polystyrene boardstock products that depend upon the low thermal conductivity of CFCs for superior insulating properties.

6.3.1 Processing Considerations

The blowing agent for polystyrene foam should be chemically stable under the operating conditions present during polystyrene manufacturing. For purposes of consistent product quality, it is essential that the blowing agent not react with any of the foam ingredients. It is equally important that the blowing agent is not easily thermally decomposed to retain foam integrity during the processing steps.[29]

To be effective as a blowing agent for extruded use, a compound must have an appropriate vapor pressure in the molten resin at the point of extrusion. In most cases, this vapor pressure should be at least 670 psia at extrusion temperature. This limits blowing agents for most resins to those with boiling points from -40°C to +50°C (-40°F to +122°F). If the boiling point is too low, the blowing agent would not be an easily compressed vapor; therefore, it would be difficult to meter into the extruder. Conversely, if the boiling point is too high, the vapor bubbles will expand too slowly or not at all.

Because extruded polystyrene foam production requires the presence of a blowing agent, the permeability of the blowing agent through the polymer is an important factor. Permeability is a function of the blowing agent's diffusivity through the polymer, its solubility in the polymer, aging characteristics, and rate of air infusion. If either the diffusivity or the solubility is too high, thermoforming will be difficult, because there will not be enough blowing agent retained in the foam cells. High solubility and/or diffusivity would also make potential substitutes unsuitable for manufacture of polystyrene insulating boardstock. If the blowing agent escapes through the foam cells, the valuable insulating properties would be lost. In fact, because most of the blowing agent should be retained in the foam for the entire life of the product (i.e., 20 years or more), diffusion rates should be very small to ensure long-term product performance. There is a controversy within the foam insulation board industry as to the relative longevity of insulating characteristics for the different foam products.

The quantity of blowing agent required to make a given foam is a function of the agent's molecular weight and gas efficiency.[30] For a blowing agent, the gas efficiency equals the actual contribution to cell volume divided by the total volume of gas required. The efficiency is a measure of the amount of blowing agent used that actually contributes to product expansion. A good blowing agent for polystyrene foam should have a gas efficiency greater than 90 percent.

Blowing agents for EPS foam should have a high enough molecular weight not to vaporize at ambient air pressure during aging and storage of impregnated beads. At the same time, the molecular weight must be low enough to vaporize during bead expansion. Pentane is the only blowing agent that satisfies both of these conditions.

Fire hazards are associated with using hydrocarbon blowing agents. However, the flammability of the foam product is more a function of the flammability of the polymer than that of the blowing agent trapped in the foam cells.[31] Although it is certainly preferable that a blowing agent be nonflammable, it is possible to manufacture foams safely with a flammable blowing agent, such as pentane, given proper equipment and sufficiently trained personnel. This is supported by the fact that some major producers of thermoformable PSF sheet and virtually all producers of EPS beads use hydrocarbons as their primary blowing agents. Dilution of flammable

emissions with adequate ventilation is the primary safety precaution taken.

6.3.2 Product Considerations

Most PSF sheet is used for packaging or serving food products. Meat trays, egg cartons, hamburger shells, and disposable plates are examples of this application. Because some blowing agent is retained in the final foam product and these products come in direct contact with food stuffs, the Food and Drug Administration (FDA) must approve any new chemical which would be used as a blowing agent. Prior to such approval, a candidate substitute blowing agent has to undergo extensive toxicity testing, and even a slight degree of toxicity would jeopardize FDA acceptance of a potential alternative compound.[32]

Polystyrene foam boardstock is used primarily as an insulating material for residential and commercial structures. In these applications, polystyrene boardstock has the advantage of high insulating quality (per thickness) due to the CFC vapor trapped in the cells. An alternative blowing agent with lower insulating capability (i.e., higher thermal conductivity) could be used, but the material's competitive advantage would be lessened in the building materials market. Thus, an optimum substitute would possess insulating qualities similar to or better than those of CFC-12. For use in the construction industry, the product must meet flammability standards. The use of hydrocarbons as blowing agents may cause problems in this respect.

6.3.3 Available Alternatives

Although PSF products have traditionally been produced with CFC-11, CFC-12, or hydrocarbon blowing agents, four alternative HCFCs exist as potential replacements. These are HCFC-22, HCFC-124, HFC-134a, and HCFC-142b. HCFC, the so-called "soft CFC", and HFC are not fully halogenated and consequently have significantly less ozone depletion potential. Characteristics of these alternatives are presented in Table 6-1. Table 6-2 shows blowing agent alternatives by end product. HCFC-22 and HCFC-142b are currently commercially available, and HCFC-22 is now being used in many extruded PSF sheet facilities. The Foodservice and Packaging Institute recently announced that, in response to the Montreal Protocol, HCFC-22 has completely replaced CFC-11 and CFC-12 in extruded PSF sheet for the food packaging industry. It is used either alone or in combination with about 30 percent pentane in sheet extrusion.[33] The HCFC-124 and HFC-134a blowing agents are expected to be commercially

TABLE 6-1. EVALUATION FACTORS FOR SOFT CFC POLYSTYRENE FOAM BLOWING AGENTS[34]

Factors	CFC-12	Alternative CFC Blowing Agents			
		HCFC-22	HCFC-124	HFC-134a	HCFC-142b
Reactivity with Ingredients	None	None	None	None	None
Stability	Stable	Stable	Stable	Stable	Stable
Boiling Point, 11°C (°F)	-29.8 (-21.6)	-40.8 (-41.4)	-11 (12.2)	-26.3 (-15.3)	-9.2 (15.4)
Solvent Power	Low	Low	Low	Low	Moderate
Gas Efficiency (% of theory)	90+	Low	90	95	80
Molecular Weight	120.9	86.5	136.5	102.0	100.5
Quantity for 0.08 g/cm^3 (5 lb/ft^3) Foam (parts/100 parts resin)	5	NA	6	4.2	5
Thermal Conductivity W/m-°C (Btu/hr-ft-°F)	0.0097 (0.0056)	0.0105 (0.0061)	0.0102 (0.0059)	0.0083 (0.0048)	0.0111 (0.0064)
Diffusivity Through Polymer	Low	High	Low	Low	Moderate
Toxicity	Low	Low	Incomplete	Incomplete	Low
Flammability[a]	Non-flammable	Non-flammable	Non-flammable	Non-flammable	Slightly flammable
Ozone Depletion Factor	1.0	0.05	0.02	No chlorine[b]	0.06
Commercial Production	Yes	Yes	In development	In development	Yes
FDA Approval	Yes	Yes	Not assessed	Not assessed	Yes

NA - Not available
[a]These estimates are made qualitatively relative to CFC-12.
[b]Not included in ozone depletion estimate because compound contains no chlorine.

TABLE 6-2. ALTERNATIVE BLOWING AGENTS BY END PRODUCT[38]

End Product	Current Blowing Agent	Alternative Blowing Agent
Extruded Polystyrene	VOC (Pentane, Butane) CFC-12 combination	HCFC-22, HCFC-142b, HFC-134a, CO_2/VOC
Loose Fill Packaging	VOC (Pentane, Butane) CFC-11, CFC-12	HCFC-22, HCFC-142b, HFC-134a
Expandable Polystyrene (EPS)	Pentane	CO_2/VOC combination

available by mid-1992.[36] Performance of these two alternatives is not fully proven, nor are they approved for food packaging uses.[37]

The use of HCFCs and HFCs as PSF blowing agents could theoretically eliminate VOC emissions from the industry. However, as discussed above, product quality and performance would be affected. In addition, the availability of alternative blowing agents has been questionable in the recent past. Suppliers of soft CFCs are apparently hesitant to commit to HCFC production in light of their uncertain regulatory status.

For extruded PSF board, HCFC-142b is an acceptable alternative and is currently used by at least one major board producer.[38] The HCFC-142b is combined with approximately 25 percent pentane for foam board blowing purposes. However, there is reportedly an availability problem with HCFC-142b.[39] HFC-134a is also a viable alternative for extruded PSF board. Fripp Fibre Foams has developed a foam product using HFC-134a that compares favorably to foam blown with HCFC-22, and requires smaller amounts of blowing agent per product unit than does HCFC-22. However, HFC-134a costs approximately three to five times as much as HCFC-22.[40]

N-pentane (C_5H_{12}) is the primary hydrocarbon blowing agent currently in use. Isopentane and n-butane are alternatives to this blowing agent that have been used sparingly. Other hydrocarbons do not exhibit the same suitable characteristics required of blowing agents. Butane (C_4H_{10}) and lower molecular weight hydrocarbons exist as gases at room temperature and are difficult to handle and meter during processing. Hexane (C_6H_{14}) and higher molecular weight hydrocarbons have higher boiling points and lower vapor pressures.

Blends of hydrocarbons and soft CFC offer promising options to the PSF industry for reducing VOC and CFC emissions. Maintaining a certain percentage of hydrocarbon in blowing agents may help to preserve product quality; the soft CFCs appear to be an improvement for both stratospheric and ground-level ozone concerns.[41] Current industry developments indicate that soft CFC-VOC combinations are viable blowing agent alternatives due to their costs, availability, and relative environmental acceptability. However, uncertainty concerning the regulatory status of soft CFCs is still a significant barrier to their further use.

Combinations of CO_2 and pentane are used successfully in sheet extrusion. Because of CO_2's high diffusion rate, fugitive pentane emissions are reduced and a greater proportion of pentane is lost during

the reclaim process where it can be more effectively controlled. Industry data indicate that pentane emissions can be reduced by 35 percent when pentane blowing agent is replaced with 25 percent CO_2.[42]

CO_2 is also used in the manufacture of expandable beads, reducing the amount of pentane needed as a blowing agent (low pentane beads).[43] The use of low pentane beads (<6.5 percent pentane) has been mandated by the State of Georgia Department of Natural Resources, Environmental Protection Division in several compliance schedules.[44] The compliance schedules require low pentane beads with no greater than 5.35 percent pentane to be phased in by July, 1991. A major disadvantage to the use of CO_2 as a blowing agent in expandable beads is its extremely fugitive nature, requiring EPS bead products to be reblown after pre-expansion.[45]

Due to the resource constraints of this study, alternate blowing agents are not included in the model facility cost estimates in Section 7.0; however, they are clearly a feasible control option for some PSF facilities. (No instances were found of EPS bead processes using blowing agents other than 100 percent pentane.) Some estimates of the costs associated with switching blowing agents are available through industry contacts. The Foodservice and Packaging Institute estimates that switching from CFC-11 or CFC-12 to HCFC-22 incurs capital costs of about $100,000 for an average size facility.[46] An Institute representative also cited a United Nations Environmental Programme report estimating capital costs of $50,000 per plant for switching blowing agents. Within the PSF food packaging industry, egg carton production is considerably more complex than other processes, and would probably incur the higher estimated costs.[45] A large sheet facility reports having switched from pentane to HCFC-22 as their primary blowing agent at a cost of $60,000, including lost production, operator training, and time spent by researchers.[48] However, this facility reports that the cost of HCFC-22 is approximately five to six times that of pentane.

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7.0 CONTROL COSTS

This chapter presents costs for controlling VOC emissions from the EPS bead and PSF sheet model plants presented in Section 5.0, "Process Emissions". Control costs for PSF extruded board facilities were not developed because these facilities predominately use CFCs or HCFCs, not hydrocarbons (VOC). The annual production rates of the model facilities are based on model facilities developed in the California South Coast Air Quality Management District Proposed Rule 1175 and a Society of Plastics Industry conference paper.[1,2,3] A small, medium, and large model facility for each process is included (1,500, 3,000, 4,500 tpy for ESP; 1,000, 5,000, 10,500 tpy for extruded sheet).

Thermal incineration and carbon adsorption are the VOC control technologies for which costs are presented. Three general groups of control devices were discussed in detail in Section 6.0, "Emissions Control Techniques": incineration, adsorption systems, and alternate technologies.

7.1 COST ASSUMPTIONS

Thermal incineration and carbon adsorption costs were estimated using the methods presented in the EPA Office of Air Quality Planning and Standards (OAQPS) Control Cost Manual (EPA 450/3-90-006, January 1990).[4] Different costing procedures may produce different results. Industry reports of the cost effectiveness of these control technologies vary widely, and illustrate the fact that many capital and operating costs are plant-specific. Installed ductwork costs were estimated using the method of Vatavuk and Neveril.[5] Installed fan costs for the capture system were estimated using the Richardson Estimating Standards.[6] Each model plant was estimated to require 3000 feet of 1/8-inch thick carbon steel ductwork for routing captured emissions to the control device. Actual ductwork construction and length will vary on a plant-to-plant basis. The feasibility and costs of venting VOC emissions to existing boilers are also

discussed. The costs presented in this report are study-level cost estimates of ±30 percent accuracy, as applied to the model facilities. All costs are in 1988 dollars.

The VOC losses resulting from storage of finished products were not considered in the cost analyses. It is assumed that only those VOC losses occurring during production are controlled. Storage losses were not addressed because individual facilities will have a wide range of storage configurations that a limited number of model plants cannot accurately address. High capture efficiency may be achieved in storage facilities where, for example, total enclosure is possible, or where the exhaust stream can be cascaded or recirculated. However, under less optimal conditions, higher flow rates and lower capture efficiencies would be expected in storage areas. Therefore, the overall cost effectiveness of controlling storage losses is expected to be high relative to the amount of emission reduction achieved.

In many cases, preliminary engineering work is required to design the capture and control systems. For purposes of these cost estimates, engineering costs are estimated at 30 percent of the purchased equipment costs.[7] The amount of engineering time required will depend on the availability of information, as well as the size and layout of the facility. Large facilities may have staff engineers to perform preliminary design efforts, while small facilities may have to hire outside engineering firms.

Capture efficiencies in the range of 50 to 75 percent are believed to be representative of capture efficiency corresponding to a well-designed capture system. It might be possible to achieve up to 100 percent capture efficiency for those cases where VOCs can be piped directly from the emission source to a control device. Costs for the three PSF sheet model facilities assume 100 percent capture of scrap/repelletizing emissions based on hard piping the emissions directly to the control device (i.e., carbon absorption or thermal incineration). Cost for the three EPS model facilities assumes 60 percent capture efficiency of manufacturing emissions. Additional cost analyses were prepared for the EPS model facilities using 50 and 75 percent capture efficiencies. These additional analyses provided a general indication of the impact of capture efficiency on cost effectiveness of capture and control.

Where hoods are used as the primary capture device, an efficiency as high as 75 percent or higher may be achieved. As described in Section 6.0, different processes afford different opportunities for capturing emissions. Capture efficiencies of 75 percent and higher are more likely for certain emissions points, such as scrap grinding units, than for less easily contained processes, such as molding lines or thermoforming units. Actual capture efficiency will depend on the hood design. Capture efficiencies of 75 percent or more will be obtained only in those cases where the hood is designed for a specific application.[8]

Additionally, accurate estimates of variables such as pollutant concentration and required air flow rates must be determined. Any change occurring in these variables after the hood has been installed can drastically reduce hood efficiency.[9] It is desirable to achieve the highest capture efficiency possible. A higher capture efficiency will produce a lower waste gas stream flow rate because less air is required to pull the same amount of pollutant into the capture and control system. A lower air flow rate results in a less expensive control system.

Thermal incineration costs are based on installing units equipped with a heat exchanger rated at 70 percent heat recovery. An estimate of 70 percent heat recovery is used since it is the highest heat recovery considered reasonable by the OAQPS Control Cost Manual.[10] The destruction efficiency is assumed to be 98 percent, corresponding to an incineration temperature of 1600°F and a nominal residence time of 0.75 seconds.[11]

Carbon adsorption efficiency is assumed to be an average of 90 percent over the lifetime of the carbon bed. Short term carbon adsorption may be 95 percent or higher, but a more realistic time weighted average is 90 percent. Annualized costs of carbon adsorption include recovery credits. These credits are based on reuse for the PSF sheet model plants and use as fuel in process steam boilers in the EPS bead model plants. It is assumed that the VOC will not be disposed of as hazardous waste. Disposal costs can range from $0.15 to $0.50 per pound, not including transportation, which may vary with geographic location.[12]

Finally, all model plants are assumed to operate on an 8400 hours per year schedule (50 weeks per year, 7 days per week, 24 hours per day). Many small PSF facilities, particularly small EPS bead facilities, do not operate continuously. Again, the variety of actual existing operating

conditions cannot all be reflected in these cost estimates. All other assumptions are stated in the OAQPS Control Cost Manual and are not discussed in this document.

An additional consideration is the control of emissions at facilities where VOC/CFC or VOC/HCFC mixtures are used as blowing agents. The costs reported here reflect the control of VOC emissions only. Halogenated compounds such as CFCs and HCFCs can produce combustion products such as hydrochloric and hydrofluoric acids, and may require the use of corrosion-resistant materials and additional flue gas treatment. In carbon adsorption, a larger bed volume may be required to achieve the same removal efficiency when a mixture of blowing agents is used, since the adsorptive capacity of carbon is typically less for halogenated compounds compared to pentane. These considerations can cause significant increases in control costs.

7.2 CONTROL COSTS

Tables 7-1 and 7-2 present emission reductions and cost estimates for applying carbon adsorption and thermal incineration VOC control devices to the EPS and PSF sheet model facilities. As discussed earlier, these costs assume 100 percent capture of scrap/repelletizing emissions from the PSF sheet model plants and 60 percent capture of manufacturing emissions from the EPS model plants. These tables indicate that carbon adsorption may be more cost effective than thermal incineration. The estimated annual costs of incineration are significantly higher than carbon adsorption. For the model facilities, the annualized costs of thermal incineration range from approximately 1.7 to 3.4 times those of carbon adsorption. The waste gas heat content ranges from approximately 5 to 9 BTU per pound. Therefore, large amounts of auxiliary fuel are required to operate the incinerator to achieve effective VOC reductions. This accounts for a major portion of the annualized costs of thermal incineration.

The cost effectiveness of thermal incineration with 70 percent heat recovery ranges from $4,405 to $6,950 per ton for the model EPS facilities and from $4,050 to $11,100 per ton for the model PSF sheet facilities.

The cost effectiveness of carbon adsorption is estimated to be $1,405, $2,010, and $3,330 per ton for the large, medium, and small model EPS

TABLE 7-1. CONTROL BY CARBON ADSORPTION

Plant Type	Plant Size (ton/yr)	Blowing Agent (BA) Used			BA Manufacturing Releases		Overall BA Captured[a]		Overall BA Reduction[b]		Total Capital Investment[c]	Total[c] Annualized Cost	Cost Effectiveness ($/ton)
		Type	%	Amount (tons/yr)	% of BA Released	Amount (ton/yr)	%	Amount (ton/yr)	%	Amount (tpy)			
EPS	1,500	Pentane	6.0	90	60	54	36	32	32	29	246,030	96,470[d]	3,330
	3,000	Pentane	6.0	180	60	108	36	65	32	58.	344,190	116,580[d]	2,010
	4,500	Pentane	6.0	270	60	162	36	97	32	87	414,060	122,300[d]	1,405
PSF Sheet	1,000	Pentane	4.8	48	55	26	35	17	32	15	283,020	101,790[e]	6,790
	5,000	Pentane	4.8	240	55	132	35	84	32	76	640,060	166,320[e]	2,190
	10,500	Pentane	4.8	504	55	276	35	176	32	158	971,214	204,120[e]	1,290

[a]Assumes 60 percent capture of manufacturing emissions from EPS model plants and 100 percent capture of scrap grinding/repelletizing emissions from PSF sheet model plants. Scrap grinding/repelletizing emissions are estimated to be 35 percent of the blowing agent content (See Table 5-2).
[b]Assumes 90 percent recovery of captured emissions.
[c]1982 dollars.
[d]Includes recovery credit for use of recovered pentane as fuel in process steam boiler.
[e]Includes recovery credit for reuse of pentane in manufacturing process.

TABLE 7-2. CONTROL BY THERMAL INCINERATION

Plant Type	Plant Size (ton/yr)	Blowing Agent (BA) Used			BA Manufacturing Releases		Overall BA Captured[a]		Overall BA Reduction[b]		Total Capital Investment[c]	Total Annualized Cost[c]	Cost Effectiveness ($/ton)
		Type	%	Amount (tons/yr)	% of BA Released	Amount (ton/yr)	%	Amount (ton/yr)	%	Amount (tpy)			
EPS	1,500	Pentane	6.0	90	60	54	36	32	32	31.4	433,715	218,230	6,950
	3,000	Pentane	6.0	180	60	108	36	65	32	63.7	534,990	319,890	5,020
	4,500	Pentane	6.0	270	60	162	36	97	32	95.1	609,600	418,950	4,405
PSF Sheet	1,000	Pentane	4.8	48	55	26	35	17	34	16	437,219	177,550	11,100
	5,000	Pentane	4.8	240	55	132	35	84	34	82	779,740	414,510	5,055
	10,500	Pentane	4.8	503	55	276	35	176	34	172	1,037,600	696,795	4,050

[a]Assumes 60 percent capture of manufacturing emissions from EPS model plants and 100 percent capture of scrap grinding/repelletizing emissions from PSF model plants. Scrap grinding/repelletizing emissions are estimated to be 35 percent of the blowing agent content. (See Table 5-2)

[b]Assumes 98 percent destruction of captured emissions.

[c]1988 dollars.

plants, respectively. Cost effectiveness for the large, medium, and small model PSF sheet plants are $1,290, $2,190, and $6,790 per ton, respectively.

As facilities decrease in size, the cost effectiveness ratio increases, since the amount of VOC controlled decreases faster than the annualized costs. Additionally, some facilities may have a capital worth approximately equal to or less than the capital investment required to purchase control equipment.[13] Therefore, it is important to consider annualized costs and the total capital investment in addition to the cost effectiveness when determining whether controls should be required.

7.3 EFFECT OF CAPTURE EFFICIENCY ON COSTS

The cost effectiveness of the control technologies evaluated vary with the capture efficiency associated with the different process operations. While the capture efficiency for each operation may be dependent upon the physical arrangement of equipment and mechanisms of emissions release, an overall plant-wide capture efficiency was used in the calculations performed in this study.

Capture efficiency is a function of the capture device inlet velocity (face velocity) and the degree to which an emission source is enclosed by the capture device. Capture efficiency is increased when the face velocity or the degree of enclosure is increased. There are two ways to increase the face velocity or the degree of enclosure and, therefore, the capture efficiency: by increasing the air flow into the capture system, or by decreasing the area between and perpendicular to the emission source and the capture device (face area). In complete enclosure, the face area is zero because the emission source is inside the collection device.

The costs of control devices are directly affected by increases in the amount of gas to be treated. The resulting increase in capital and annualized costs is likely to outweigh any increase in capture efficiency. Therefore, the net result will be an increase in the cost effectiveness ratio.

The face area may be decreased by moving the capture device inlet, such as a hood, closer to the VOC emission source. The face area decreases, but the volumetric flow rate of the air into the capture system

remains constant. Since the same volume of air enters the capture system through a smaller area, the face velocity, and correspondingly the capture efficiency, increases. The cost effectiveness ratio decreases because more VOC is captured at the same capital operating costs. However, it may not be possible to install new hoods or move existing hoods closer to equipment in existing facilities due to space limitations. Fully enclosing the emission will increase capture efficiency but is more expensive and may be technically difficult.

Carbon adsorption and thermal incineration costs are presented for capture efficiencies of 50 and 75 percent for the model EPS facilities in Tables 7-3 through 7-6. The cost effectiveness ratios for the EPS model facilities at 50, 60, and 75 percent capture efficiencies are summarized in Table 7-7. For each model facility the percent difference in cost effectiveness between 50 and 75 percent capture efficiencies range from 27 to 32 percent for carbon adsorption, and 34 to 35 percent for thermal incineration. The range of percent differences in cost effectiveness is wider for carbon adsorption than for thermal incineration. There are two main factors which account for the percent difference in costs of carbon adsorption control at various control efficiencies. These factors are amount of VOC controlled and the capital cost of the capture/control system. A higher capture efficiency will require more carbon to adsorb the additional VOC. More carbon requires a larger carbon adsorber unit and a correspondingly larger capital investment. However, the increase in capital cost is more than offset by the additional recovery of blowing agent, and the net result is a lower cost effectiveness ratio.

The amount of VOC controlled is the primary factor affecting the cost of thermal incineration. The percent difference in cost effectiveness is, therefore, almost unaffected by facility size. Although slight differences in auxiliary fuel requirements do occur with differences in capture efficiency, the effect on capital cost if negligible.

The cost analysis indicates that, for EPS facilities ranging from 1500 to 4,500 tpy, carbon adsorption may be more cost effective than thermal incineration at capture efficiencies of 50, 60, and 75 percent. For both carbon adsorption and thermal incineration, the higher the capture efficiency, the better the cost effectiveness ratio. A similar analysis of PSF sheet extrusion is expected to show the same results, since the same

TABLE 7-3. EPS MODEL FACILITIES CONTROL BY CARBON ADSORPTION AT 50 PERCENT CAPTURE EFFICIENCY

Plant Type	Plant Size (ton/yr)	Blowing Agent (BA) Used			BA Manufacturing Releases		Overall BA Captured[a]		Overall BA Reduction[b]		Total Capital Investment[c]	Total Annualized Cost[c]	Cost Effectiveness ($/ton)
		Type	%	Amount (tons/yr)	% of BA Released	Amount (ton/yr)	%	Amount (ton/yr)	%	Amount (tpy)			
EPS	1,500	Pentane	6.0	90	60	54	30	27	15	27	241,000	95,970[d]	4,000
	3,000	Pentane	6.0	180	60	108	30	54	15	49	336,950	116,150[d]	2,370
	4,500	Pentane	6.0	270	60	162	30	81	15	73	399,100	121,500[d]	1,665

[a]Assumes 50 percent capture of manufacturing emissions.
[b]Assumes 90 percent recovery of captured emissions.
[c]1988 dollars.
[d]Included recovery credit for use of recovered pentane as fuel in process steam boiler.

TABLE 7-4. EPS MODEL FACILITIES CONTROL BY THERMAL INCINERATION AT 50 PERCENT CAPTURE EFFICIENCY

Plant Type	Plant Size (ton/yr)	Blowing Agent (BA) Used			BA Manufacturing Releases		Overall BA Captured[a]		Overall BA Reduction[b]		Total Capital Investment[c]	Total Annualized Cost[c]	Cost Effectiveness ($/ton)
		Type	%	Amount (tons/yr)	% of BA Released	Amount (ton/yr)	%	Amount (ton/yr)	%	Amount (tpy)			
EPS	1,500	Pentane	6.0	90	60	54	30	27	29	26.5	432,170	218,240	8,235
	3,000	Pentane	6.0	180	60	108	30	54	29	52.9	532,980	320,130	6,050
	4,500	Pentane	6.0	270	60	162	30	81	29	79.4	607,250	419,450	5,280

[a]Assumes 60 percent capture of manufacturing emissions.
[b]Assumes 98 percent destruction of captured emissions.
[c]1988 dollars.

TABLE 7-5. EPS MODEL FACILITIES CONTROL BY CARBON ADSORPTION AT 75 PERCENT CAPTURE EFFICIENCY

Plant Type	Plant Size (ton/yr)	Blowing Agent (BA) Used			BA Manufacturing Releases		Overall BA Captured[a]		Overall BA Reduction[b]		Total Capital Investment[c]	Total Annualized Cost[c]	Cost Effectiveness ($/ton)
		Type	%	Amount (tons/yr)	% of BA Released	Amount (ton/yr)	%	Amount (ton/yr)	%	Amount (tpy)			
EPS	1,500	Pentane	6.0	90	60	54	45	41	41	37	262,630	100,630	2,720
	3,000	Pentane	6.0	180	60	108	45	81	41	73	369,440	123,300	1,690
	4,500	Pentane	6.0	270	60	162	45	122	41	110	476,740	133,840	1,220

[a]Assumes 75 percent capture of manufacturing emissions.
[b]Assumes 90 percent recovery of captured emissions.
[c]1988 dollars.

TABLE 7-6. EPS MODEL FACILITIES CONTROL BY THERMAL INCINERATION AT 75 PERCENT CAPTURE EFFICIENCY

Plant Type	Plant Size (ton/yr)	Blowing Agent (BA) Used			BA Manufacturing Releases		Overall BA Captured[a]		Overall BA Reduction[b]		Total Capital Investment[c]	Total Annualized Cost[c]	Cost Effectiveness ($/ton)
		Type	%	Amount (tons/yr)	% of BA Released	Amount (ton/yr)	%	Amount (ton/yr)	%	Amount (tpy)			
EPS	1,500	Pentane	6.0	90	60	54	45	41	0.44	40.2	432,140	216,210	5,380
	3,000	Pentane	6.0	180	60	108	45	81	0.44	79.4	532,940	316,080	3,980
	4,500	Pentane	6.0	270	60	162	45	122	0.44	119.6	607,210	413,370	3,460

[a]Assumes 75 percent capture of manufacturing emissions.
[b]Assumes 98 percent destruction of captured emissions.
[c]1988 dollars.

TABLE 7-7. COST EFFECTIVENESS ($/TON) AT 50, 60, AND 75 PERCENT CAPTURE EFFICIENCIES - EPS MODEL FACILITIES

Plant Size (tons/yr)	Carbon Adsorption Capture Efficiency			Thermal Incineration Capture Efficiency		
	50	60	75	50	60	75
1,500	4,000	3,330	2,720	8,235	6,925	5,380
3,000	2,370	2,010	1,690	6,050	5,000	3,980
4,500	1,665	1,405	1,220	5,280	4,385	3,460

driving forces would affect capture efficiencies and cost effectiveness. However, the use of existing boilers as VOC controls may have substantial effects on the thermal incineration cost effectiveness figures.

7.4 USE OF EXISTING BOILERS

Most EPS facilities will have existing boilers for process steam production. If it is feasible to use existing boilers as VOC controls, the only required capital investments involved are the ductwork, fans, dampers, and controls required to capture the emissions and vent them to the boiler.

The estimated annualized costs of installing 3000 feet of ductwork and a single fan meeting the air flow requirements for each of the EPS model facilities are presented in Table 7-8. Capital costs were estimated using the method of Vatavuk and Neveril for the ductwork and the Richardson Estimating Standards for the fan requirements.[14, 15] Capital cost factors from the OAQPS Control Cost Manual were then applied to estimate the annual costs.[16] As discussed above, capture device design and installation are site specific, and cost data are not available; therefore, costs for capture devices (i.e., hoods or enclosures) are not included in these figures.

The total annualized costs for ductwork range from 23 to 39 percent of the total annualized costs required to apply carbon adsorption to the model EPS facilities. Thus, substantial savings may be obtainable if existing boilers can be used as control devices. The feasibility and cost effectiveness of using existing boilers as control devices are difficult to assess. This will depend on the capacity and number of the existing boilers, required fuel to air ratio, and the operating temperature. In some facilities, these limitations may preclude the use of existing boilers as control devices. However, where this control strategy is feasible, higher VOC destruction efficiencies may be obtained compared to carbon adsorption, depending on design constraints.

TABLE 7-8. ESTIMATED DUCT COST - 3000 FEET

Plant Type	Plant Size (ton/yr)	Total Investment Cost ($)	Total Annualized Cost ($)
EPS	1,500	200,840	47,100
	3,000	291,220	71,595
	4,500	364,650	92,860

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9. See reference 8.

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12. Telecon. Bagley, C., Radian Corporation with Henderson, G., GSX, Inc. March 21, 1990. Conversation regarding waste disposal costs.

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15. See Reference 6.

16. See Reference 4.

APPENDIX A

COMPANIES INVOLVED IN MANUFACTURING OF PS FOAM PRODUCTS

Company Name	Location	EPS Beads	PS Sheet	PS Board

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COMPANIES INVOLVED IN MANUFACTURING OF PS FOAM PRODUCTS

Company Name	Location	EPS Beads	PS Sheet	PS Board
Accurate Foam Co.	La Porte, IN	X	X	
Advance Foam Plastics, Inc.	Denver, CO	X	X	X
Airlite Plastics Co.	Omaha, NB			
Alamo Foam, Inc.	San Antonio, TX		X	X
Albany International	Agawam, MA			
Alcoa Building Products, Inc.	Pittsburgh, PA			
All American Enterprises	Albuquerque, NM	X		X
Allied Foam Products, Inc.	Gainesville, GA			X
All-Pak, Inc.	Pittsburgh, PA		X	
Alsco Arco Building Products	Akron, OH			
American Excelsior Co.	Arlington, TX	X	X	
American Foam Products	Painsville, OH	X	X	
Amoco	Beech Island, SC			
Amoco	Chippawa Falls, WI			
Amoco	Lamirada, CA			
Amoco	Winchester, VA			
Amotex Plastics	Nashville, TN			
Amxco, Inc.	Arlington, TX			
ARCO Chemical Company	Newtown Sq., PA	X		
Argent Corp.	Novi, MI	X	X	
Arkansas Plastics	Sulphur Springs, AR			X
Arvron, Inc.	Grand Rapids, MI	X		X
Ashland Chemical Co.	Dublin, OH	X		
Astrofoam Molding Co., Inc.	Chetsworth, CA	X		
Atlas Industries	Ayer, MA			
BASF Corp.	Parsippany, NJ	X		
Berstoff Corp.	Charlotte, NC		X	
Bird, Inc., Vinyl Products	Bardstown, KY			
Burnett Associates, Ltd.	Syracuse, NY		X	X
Burton Packaging Co., Inc.	Haspeth, NY			
Cellofoam/Southeastern	Conyers, GA			X
Cellox Corporation	Reedsburg, WI			
Cellular Packaging Co.	Auburn, WA	X		
Century Insulation Mfg., Co.	Union, MS	X	X	X
Chemtech International Co.	Houston, TX	X		
Chestnut Ridge Foam, Inc.	Latrobe, PA		X	
Cincinnati Foam Products, Inc.	Cincinnati, OH	X	X	
Commodore Plastics	Holcomb, NY			
CONPROCO Corp.	Concord, NH			X
Contour Products	Kansas City, KS		X	X
Corrugated Paper Products, Inc.	Amityville, NY	X	X	

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Company Name	Location	EPS Beads	PS Sheet	PS Board
Crystal X Corporation	Darby, PA			
Custom Pack Inc.	Malvern, PA	X		
Dart Container Corporation	Corona, CA			
Dart Container Corporation	Horse Cave, KY			
Dart Container Corporation	Lavonia, GA			
Dart Container Corporation	Leola, PA			
Dart Container Corporation	Lodi, CA			
Dart Container Corporation	Mason, MI			
Dart Container Corporation	Plant City, FL			
Dart Container Corporation	Tumwater, WA			
Dart Container Corporation	Waxahachie, TX			
Davis Core and Pad Co.	Cave Spring, GA	X		X
Delta Foam Products Co.	Los Angeles, CA	X		X
Denver Plastics, Inc.	Hudson, CO			
Dipak Manf. Co., Inc.	Westport, NY			
Diversified Foam, Inc.	Yadkinville, NC	X	X	
Diversified Plastics Corp.	Nixa, MO	X		X
Diversifoam Products Inc.	New Brighton, MN	X	X	X
Dixie/Marathon	Baltimore, MD			
Dixie/Marathon	St. Louis, MO			
Dow Chemical Co., USA	Allyn's Point, CT			
Dow Chemical Co., USA	Carteret, NJ			
Dow Chemical Co., USA	Hanging Rock, OH			
Dow Chemical Co., USA	Joliet, IL			
Dow Chemical Co., USA	Magnolia, AR			
Dow Chemical Co., USA	Midland, MI	X	X	X
Dow Chemical Co., USA	Pevely, MO			
Dow Chemical Co., USA	Seattle, WA			
Dow Chemical Co., USA	Torrance, CA			
Drew Foam Companies, Inc.	Monticello, AR			X
Drew Foam Division	Denver, CO			X
Dyplest Foam Insulation, Ind.	Miami, FL			X
Dyrelite Corporation	New Bedford, MA			
EFP Corp.	Elkhart, IN	X	X	X
Epallon Foam Corp.	Azusa, CA			X
EPS Molding, Inc.	Houston, TX		X	X
E. R. Carpenter	Fogelsville, PA	X		
Erie Foam Products, Inc.	Erie, PA			
Expanded Plastics, Inc.	Fenton, MI	X		X
Falcon Manf., Inc.	Byron Center, MI			X
Flextron Industries, Inc.	Aston, PA	X	X	
Florida Pak	Ocala, FL	X		

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COMPANIES INVOLVED IN MANUFACTURING OF PS FOAM PRODUCTS

Company Name	Location	EPS Beads	PS Sheet	PS Board
Foam Fabricators, Inc.	Bloomsburg, PA			
Foam Fabricators, Inc.	Compton, CA			
Foam Fabricators, Inc.	El Dorado Springs, MO			
Foam Fabricators, Inc.	Erie, PA			
Foam Fabricators, Inc.	Melrose Park, IL			
Foam Fabricators, Inc.	New Albany, IN			
Foam Fabricators, Inc.	St. Louis, MO			
Foam Molders and Specialties	Carritos, CA	X	X	
Foam Packaging, Ltd.	Harrison, NY	X	X	
Foam Plastics of New England	Prospect, CT		X	X
Foam Products Corp.	Maryland Heights, MO	X	X	X
Foamcor Packaging	Langhorne, PA	X	X	
Foamfab, Inc.	Mansfield, MA	X	X	
Foam-Lite Plastics, Inc.	Knoxville, TN	X		X
FPI	Vicksburg, MS			
Free-Flow Packaging Corp.	Redwood City, CA			
French Creek Products	Royersford, PA		X	X
Frostee Foam, Inc.	Antioch, IL			
Genpak	Longview, TX			
Genpak	Los Angeles, CA			
Genpak	Manchaug, MA			
Genpak	Middletown, NY			
Genpak	Montgomery, AL			
Georgia Foam, Inc.	Gainesville, GA			X
Geotech Systems Corp.	Sterling, VA			X
Gilman Brothers Co.	Gilman, CT	X	X	X
Glendale Plastics	Ludlow, MA			
Gotham Chicago Corp.	Chicago, IL			
Handi-Kup Co.	Corte Madera, CA			
Hastings Plastics Co.	Santa Monica, CA			X
Holland Industries, Inc.	Gilman, IA			
Hydra-Matic Packing Co.	Bethayres, PA	X	X	
H. Muehlstein and Co.,Inc	Greenwich, CT	X		
Industrial Rubber & Plastics Co.,	Haverhill, MA	X	X	
Insulaire, Inc.	Gainesville, GA			X
Insulated Building Systems, Inc.	Sterling, VA			X
Insulation Corp. of America	Allentown, PA	X		X
Insulation Technology Inc.	Bridgewater, MA	X		X
Insul-Board, Inc.	Erie, PA			X
International Polymers Corp.	Allentown, PA	X		
Inter-pac Packaging Corp.	Memphis, TN	X	X	

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COMPANIES INVOLVED IN MANUFACTURING OF PS FOAM PRODUCTS

Company Name	Location	EPS Beads	PS Sheet	PS Board
Jacobs Plastics, Inc.	Adrian, MI			X
James Global Service	Salinas, CA	X		
Kalamazoo Plastics	Kalamazoo, MI			
Kaneka America Corp.	New York, NY	X	X	X
Kayes Fibre/Dolco	Dallas, TX			
Kayes Fibre/Dolco	Decatur, IN			
Kayes Fibre/Dolco	Lawrenceville, GA			
Kayes Fibre/Dolco	Pico Rivera, CA			
Kayes Fibre/Dolco	Wenatchee WA			
Kohler-General Corp.	Sheboygen Falls, WI	X		X
Lakeside Plastics, Inc.	Oshkosh, WI	X	X	
LexFoam Manf., Inc.	Lexington, KY			X
Lifoam	Baltimore, MD			
Lin Manf. Company	Clinton, OK			
Linpac (Florida Container)	Seabring, FL			
Linpac (Florida Container)	Wilson, NC			
MacDonald Plastics	New Baltimore, MI			
Majeski, H., Co., Inc.	Aston, PA	X		
Mars Cup Company, Inc.	Huntington Station, NY			
Master Containers, Inc.	Mulberry, FL			
Matrix Applications Co.	Pasco, WA			X
Merryweather Foam, Inc.	Barberton, OH	X		
Merryweather Foam, Inc.	Sylacauga, AL	X		
Michigan Foam Products, Inc.	Grand Rapids, MI			X
Mid-America Industries	Mead, NE			X
Mobil Chemical Co.	Bakersfield, CA			
Mobil Chemical Co.	Canandaigua, NY			
Mobil Chemical Co.	Covington, GA			
Mobil Chemical Co.	Frankfurt, IL			
Mobil Chemical Co.	Stamford, CT		X	
Mobil Chemical Co.	Temple, TX			
Moldtek, Inc.	Rome, GA			X
Monsanto Company	St. Louis, MO			
MTC America, Inc.	New York, NY	X	X	
Netherland Rubber Co.	Cincinnati, OH	X		
North Brothers Company	Atlanta, GA			X
NPS Corp.	Perryville, MO	X		X
Nyman	E. Providence, RI			
Olsonite Corporation	Detroit, MI			
Owens-Illinois	Toledo, OH			

APPENDIX A

COMPANIES INVOLVED IN MANUFACTURING OF PS FOAM PRODUCTS

Company Name	Location	EPS Beads	PS Sheet	PS Board
Pacific Molded Foam	Long Beach, CA	X		
Packaging Alternatives Corp.	Fountain Valley, CA	X	X	X
Packaging Concepts	Zanesville, OH			X
Packaging Industries Group, Inc.	Hyannis, MA			X
Packateers, Inc.	Edgemont, PA	X	X	
PacTuCo	Goleta, CA	X		
Pac-Lite Products, Inc.	Marine City, MI	X	X	X
Pelafoam, Inc.	Richmond, CA			
Petersen, H.K., Inc.	Fairview Park, OH	X		
Pioneer Plastics	Bedford, CA			
Plasteel Corporation	Inkster, MI			
Plastic Molders, Inc.	Little Rock, AR	X	X	
Plastica Company, Inc.	Hatfield, PA			
Plastifoam	Rockville, CT			X
Plastilite Corporation	Omaha, NB			
Plasti-Kraft Corporation	Ozona, FL			
Plastronic Packaging Corp.	El Paso, TX			
Plastronic Packaging Corp.	Grand Prairie, TX			
Plastronic Packaging Corp.	Minneapolis, MN			
Plastronic Packaging Corp.	Sparta, WI			
Plastronic Packaging Corp.	Stevensville, MI	X		
Plastronic Packaging Corp.	St. Charles, IL			
Plymouth Foam Products	Plymouth, WI			X
Pollyfoam Corp.	Northbridge, MA	X	X	
Poly Foam Inc.	Lester Prairie, MN	X	X	X
Poly Molding Corp.	Haskell, NJ			
Preferred Plastics, Inc.	Putnam, CT			
Primex Plastics Corp.	West Carson, CA		X	
Radva Plastics Corp.	Norristown, PA			
Rector Insulations	Mt. Vernon, NY			
Reliable Plastics, Inc.	Dunellen, NJ	X	X	X
Rempac Foam Corp.	Clifton, NJ	X	X	
Republic Packaging Corp.	Chicago, IL	X		
Robin II, Inc.	Markesan, WI	X		
Scott Polymers, Inc.	Fort Worth, TX	X		
SF Products, Inc.	Jackson, MS			
SF Products, Inc.	Memphis, TN			
SF Products, Inc.	N. Kansas City, MO			
Shelmark Industries, Inc.	Columbus, OH			
Silvatrim Corp. of America	S. Plainfield, NJ		X	
Snow Foam Products	El Monte, CA			

APPENDIX A

COMPANIES INVOLVED IN MANUFACTURING OF PS FOAM PRODUCTS

Company Name	Location	EPS Beads	PS Sheet	PS Board
Stallman Company	Providence, RI			
Stanark Plastics, Inc.	Little Rock, AR			X
Stanga Enterprises, Inc.	Titusville, FL	X	X	
Styro-Molders Corp.	Colorado Springs, CO	X		X
Sweetheart Plastics, Inc.	Chicago, IL			
Sweetheart Plastics, Inc.	Conyers, GA			
Sweetheart Plastics, Inc.	Dallas, TX			
Sweetheart Plastics, Inc.	Los Angeles, CA			
Sweetheart Plastics, Inc.	Owings Mills, MD			
Sweetheart Plastics, Inc.	Wilmington, MA			
Tech Pak, Inc.	Peabody, MA	X		
Tekmold, Inc.	Muskegon, MI	X		
Tempo Plastic Co.	Burbank, CA	X		
Tex Styrene	New Brighton, MN			
Thermal Foams, Inc.	Buffalo, NY	X	X	
Therma-Tru Corp.	Toledo, OH		X	
Thompson Industries	Phoenix, AZ			
Topper Plastics, Inc.	Covine, CA			X
Toyad Corporation	Latrobe, PA			
TRI Manf. and Sales Co.	Lebanon, OH	X	X	X
Tri-State Foam Products, Inc.	Martinsville, VA			X
Tuscarora Plastics, Inc.	New Brighton, PA	X	X	
T.H.E.M. of New Jersey	Mount Laurel, NJ	X	X	
UC Industries, Inc.	Parsippany, NJ		X	X
UC Industries, Inc.	Rockford, IL			
UC Industries, Inc.	Tallmage, OH			
United Foam Plastics Corp.	Bridgeport, PA		X	
United Foam Plastics Corp.	Fairburn, GA		X	
United Foam Plastics Corp.	Georgetown, MA		X	
United Foam Plastics Corp.	Kissimmee, FL		X	
United Foam Plastics Corp.	Pawcatuck, CT		X	
United Foam Plastics Corp.	Somerset, NJ		X	
U.S. Mineral Products Co.	Stanhope, NJ			
Virginia Design Packaging Corp.	Suffolk, VA	X		
Western Foampak	Greensboro, NC			
Western Foampak	Malverne, AR			
Western Foampak	Oelwein, IA			
Western Foampak	Yakima, WA			
Western Insulfoam Corp.	Kent, WA			X
Wilshire Foam Products, Inc.	Carson, CA			
W.R. Grace & Co.	Indianapolis, IN			
W.R. Grace & Co.	Reading, PA			

Sources listed on following page

APPENDIX A

COMPANIES INVOLVED IN MANUFACTURING OF PS FOAM PRODUCTS

Company Name	Location	EPS Beads	PS Sheet	PS Board

Sources:

1. Society of the Plastics Industry. 1989 Membership Directory.

2. U.S. Environmental Protection Agency. Industrial Process Profiles for Environmental Use. U.S. EPA, ORD, Cincinnati, O.H., 1987.

3. Thomas Register of American Manufacturers: Products and Services. Thomas Publishing Company, New York, N.Y., 1988.

APPENDIX B

CALCULATION OF VOC EMISSION ESTIMATES FOR POLYSTYRENE FOAM BLOWING

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1. EPS FOAM BEADS

ASSUME: a) Beads are blown exclusively with VOCs (no CFCs) (Reference 2a)

INPUTS: a) 1988 Production: 5.58E+08 pounds (Reference 1)
b) Amount of VOC used for blowing: 6% of product weight (Reference 3)
c) VOC lost during processing: 85%

VOC EMISSIONS = 14,229 tons/year

2. PS FOAM SHEET

ASSUME: a) 60-70 % of all foam sheet is blown with VOC 65% (Reference 2b)

INPUTS: a) 1988 Production: 6.5E+08 pounds (Reference 1)
b) Amount VOC used for blowing: 4.8% of product weight (Reference 3)
c) VOC lost during processing: 50% (Reference 3)
d) VOC lost over 1-2 months: 50% (Reference 3)

VOC PROCESS EMISSIONS: 5062 tons/year

VOC LOST OVER 1-2 MONTHS: 5062 tons/year

TOTAL: 10,124 tons/year

SUMMARY OF VOC EMISSION ESTIMATES

Process	Emissions (TPY)
EPS Beads	14,229
Foam Sheet Blowing	10,124
	24,353

INFORMATION SOURCES

1. 1988 Production Numbers: "Resin Report 1989". Journal of Modern Plastics, January, 1989.

2. Percent of VOC vs CFCs used for blowing of different products:

   a) EPS Beads - "CFC Issue Hits Home". Modern Plastics, October, 1987.

   b) Foam Sheet - "Control Technology Overview Report: CFC Emissions From Rigid Foam Manufacturing." Prepared by Radian Corporation for the U. S. EPA. September 1987.

3. Percent of emissions occuring during processing and during curing:

   a) Letter from Charles Krutchen, Mobil Corporation, to Susan R. Wyatt, U. S. Environmental Protection Agency, May 9, 1990.

   b) Telecon. McLean J., Radian Corporation with Cooper, D., Dow Chemical Corporation, June 6, 1990. Conversation regarding PSF sheet extrusion.

   c) Letter from Val W. Fisher, Amoco Foam Products Company to Susan R. Wyatt, U. S. Environmental Protection Agency, May 7, 1990.

APPENDIX C-1. EPS BEAD PRODUCTION MODEL FACILITY (1500 TPY CAPACITY)

CARBON ADSORPTION COST ESTIMATION

DESIGN BASIS

Maximum Total Flow (cfm)	3,569
Total Solvent Usage (lbs/year)	180,000
Production Losses (%)	60
Capture Efficiency (%)	60
Control Efficiency (%)	90

Blowing Agent	Avg. Loading (lbs/hr)	Gas Conc. (ppm)	MW	Working Cap. (lb/lb of C)
Pentane	7	175	72	0.045

Adsorption Time (hrs) =	12
Desorption Time (hrs) =	1.5
Number of Beds Adsorbing =	2
Number of Beds Desorbing =	1
Total Number of Beds =	3
Carbon Requirement (lbs) =	2,777
Superficial Bed Vel. (ft/min) =	100
Carbon Bed Diameter (ft) =	4.77
Carbon Bed Length (ft) =	5.73
Carbon Bed Surface Area (ft^2) =	121

INSTALLED COST

Carbon Cost ($) =	5,554
Vessel Cost ($) =	11,343
Additional Duct Length (ft) =	1,000
Additional Duct ($) =	36,852
Total Equipment Cost ($) =	114,466
Total Purchased Equip. Cost ($) =	135,070
Installation Direct Costs ($) =	40,521
Total Direct Costs($) =	175,591

THERMAL INCINERATION COST ANALYSIS

DESIGN BASIS

Maximum Total Flow (cfm)	3,569
Total Solvent Usage (lbs/year)	180,000
Production Losses (%)	60
Capture Efficiency (%)	60
Control Efficiency (%)	98

Blowing Agent	Avg. Loading (lbs/hr)	Gas Conc. (ppm)	MW	Heat of Combustion (BTU/lb)
Pentane	7	175	72	9

Incinerator Operating Temperature (F)	1,600
Fractional Energy Recovery =	0.70
Preheater Inlet Temperature (F) =	77
Preheater Outlet Temperature (F) =	1,143
Flue Gas Outlet Temperature (F) =	534
Auxilliary Fuel Requirements (scfm) =	47
Total Flow Rate =	3,615

INSTALLED COST

Equipment Cost ($) =	165,491
Additional Duct Length (ft) =	1,000
Additional Duct ($) =	36,852
Total Equipment Cost ($) =	202,343
Total Purchased Equip. Cost ($) =	238,765
Installation Direct Costs ($) =	71,630
Total Direct Costs ($) =	310,395
Total Indirect Costs ($) =	121,770
Total Capital Investment ($) =	432,165

Total Indirect Costs ($) =	68,886
Total Capital Investment ($) =	244,477

ANNUAL COSTS

Steam Requirement (lbs/year) =	204,120
Steam Cost ($/1000 lbs) =	6.00
Steam Costs ($/year) =	1,225
Cooling Water Req. (gal/yr) =	700,132
Cooling Water Cost ($/1000 gal) =	0.20
Cooling Water Cost ($/yr) =	140
MF Electricity Req. (Kw-hr/yr) =	51,730
DF Electricity Req. (Kw-hr/yr) =	2,236
CW Electricity Req. (Kw-hr/yr) =	13,738
Total Elec. Req. (Kw-hr/yr) =	67,703
Electricity Cost ($/Kw-hr) =	0.06
Electricity Cost ($/yr) =	4,062
Carbon Replacement Cost ($) =	1,619
Operating Labor (hrs/yr) =	604
Labor Cost ($/hr) =	15
Operating Labor Cost ($/yr) =	9,056
Maintenace Labor & Mat. ($/yr) =	19,924
Total Direct Costs ($/yr) =	36,026
Equipment Life (yrs) =	10
Interest Rate (%) =	10
Capital Recovery Factor =	0.163
Capital Recovery Costs ($/yr) =	38,548
Taxes, Insurance, G&A ($) =	27,167
TOTAL ANNUALIZED COST ($) =	101,741

Recovery Credit Based on Reuse

Recovered Solvent (lb/yr)	58,320
Reuse Value of Rec. Solvent ($/lb) =	0.35
Reuse Value of Rec. Solvent ($/yr) =	20,412

ANNUAL COSTS

Power Fan Elc. (kW-hr/yr)	107,674
Electricity Cost ($/kW-hr)	0.06
Electricity Cost ($) =	6,460
Auxiliary Fuel Consumption (scfm) =	47
Auxiliary Fuel Cost ($/scf) =	0.0033
Auxiliary Fuel Cost ($) =	77,471
Operating Labor (hrs/yr)	604
Labor Cost ($/hr) =	15
Operating Labor Cost ($/yr)	9,056
Maintenance Labor & Mat. ($/yr) =	19,924
Total Direct Costs ($/yr) =	112,911
Equipment Life (yrs) =	10
Interest Rate (%) =	10
Capital Recovery Factor =	0.163
Capital Recovery Costs ($/yr) =	70,333
Taxes, Insurance, G&A ($) =	34,675
TOTAL ANNUALIZED COST ($)	217,918
Controlled emissions (tpy)	32
Cost effectiveness ($/ton)	6,863

Recovery Credit Based on Fuel Use to Replace No. 2 Fuel Oil

Recovered Solvent (gal/yr) =	8,331
Fuel Value of Rec. Solvent ($/gal) =	1.00
Fuel Value of Rec. Solvent ($/yr) =	8,331

Recovery Credit Based on Fuel Use to Replace Natural Gas

Recovered Solvent (lb/yr)	58,320
Fuel Value of Rec. Solvent ($/lb) =	0.049
Fuel Value of Rec. Solvent ($/yr) =	2,842

Controlled Emissions (tpy)	29
Cost effectiveness($/ton) (based on recovery value)	2,789
Cost effectiveness($/ton) (based on fuel value-No. 2 Fuel Oil)	3,203
Cost effectiveness($/ton) (based on fuel value-Natural Gas)	3,392

APPENDIX C-2. EPS BEAD PRODUCTION MODEL FACILITY (3000 TPY CAPACITY)

CARBON ADSORPTION COST ESTIMATION

DESIGN BASIS

Maximum Total Flow (cfm)	7,024
Total Solvent Usage (lbs/year)	360,000
Production Losses (%)	60
Capture Efficiency (%)	60
Control Efficiency (%)	90

Blowing Agent	Avg. Loading (lbs/hr)	Gas Conc. (ppm)	MW	Working Cap. (lb/lb of C)
Pentane	14	178	72	0.045

Adsorption Time (hrs) =	12
Desorption Time (hrs) =	1.5
Number of Beds Adsorbing =	2
Number of Beds Desorbing =	1
Total Number of Beds =	3
Carbon Requirement (lbs) =	5,554
Superficial Bed Vel. (ft/min) =	100
Carbon Bed Diameter (ft) =	6.69
Carbon Bed Length (ft) =	5.76
Carbon Bed Surface Area (ft^2) =	191

INSTALLED COST

Carbon Cost ($) =	11,109
Vessel Cost ($) =	16,142
Additional Duct Length (ft) =	1,000
Additional Duct ($) =	53,525
Total Equipment Cost ($) =	160,206
Total Purchased Equip. Cost ($) =	189,044
Installation Direct Costs ($) =	56,713
Total Direct Costs($) =	245,757

THERMAL INCINERATION COST ANALYSIS

DESIGN BASIS

Maximum Total Flow (cfm)	7,024
Total Solvent Usage (lbs/year)	360,000
Production Losses (%)	60
Capture Efficiency (%)	60
Control Efficiency (%)	98

Blowing Agent	Avg. Loading (lbs/hr)	Gas Conc. (ppm)	MW	Heat of Combustion (BTU/lb)
Pentane	14	178	72	9

Incinerator Operating Temperature (F)	1,600
Fractional Energy Recovery =	0.70
Preheater Inlet Temperature (F) =	77
Preheater Outlet Temperature (F) =	1,143
Flue Gas Outlet Temperature (F) =	534
Auxilliary Fuel Requirements (scfm) =	92
Total Flow Rate =	7,116

INSTALLED COST

Equipment Cost ($) =	196,017
Additional Duct Length (ft) =	1,000
Additional Duct ($) =	53,525
Total Equipment Cost ($) =	249,542
Total Purchased Equip. Cost ($) =	294,459
Installation Direct Costs ($) =	88,338
Total Direct Costs ($) =	382,797
Total Indirect Costs ($) =	150,174
Total Capital Investment ($) =	532,972

Total Indirect Costs ($) =	96,412
Total Capital Investment ($) =	342,169

ANNUAL COSTS

Steam Requirement (lbs/year) =	408,240
Steam Cost ($/1000 lbs) =	6.00
Steam Costs ($/year) =	2,449
Cooling Water Req. (gal/yr) =	1,400,263
Cooling Water Cost ($/1000 gal) =	0.20
Cooling Water Cost ($/yr) =	280
MF Electricity Req. (Kw-hr/yr) =	103,282
DF Electricity Req. (Kw-hr/yr) =	4,537
CW Electricity Req. (Kw-hr/yr) =	27,475
Total Elec. Req. (Kw-hr/yr) =	135,294
Electricity Cost ($/Kw-hr) =	0.06
Electricity Cost ($/yr) =	8,118
Carbon Replacement Cost ($) =	3,238
Operating Labor (hrs/yr) =	604
Labor Cost ($/hr) =	15
Operating Labor Cost ($/yr) =	9,056
Maintenace Labor & Mat. ($/yr) =	19,924
Total Direct Costs ($/yr) =	43,065
Equipment Life (yrs) =	10
Interest Rate (%) =	10
Capital Recovery Factor =	0.163
Capital Recovery Costs ($/yr) =	53,207
Taxes, Insurance, G&A ($) =	31,075
TOTAL ANNUALIZED COST ($) =	127,347

Recovery Credit Based on Reuse

Recovered Solvent (lb/yr)	116,640
Reuse Value of Rec. Solvent ($/lb) =	0.35
Reuse Value of Rec. Solvent ($/yr) =	40,824

ANNUAL COSTS

Power Fan Elc. (kW-hr/yr)	211,928
Electricity Cost ($/kW-hr)	0.06
Electricity Cost ($) =	12,716
Auxiliary Fuel Consumption (scfm) =	92
Auxiliary Fuel Cost ($/scf) =	0.0033
Auxiliary Fuel Cost ($) =	152,344
Operating Labor (hrs/yr)	604
Labor Cost ($/hr) =	15
Operating Labor Cost ($/yr)	9,056
Maintenance Labor & Mat. ($/yr) =	19,924
Total Direct Costs ($/yr) =	194,040
Equipment Life (yrs) =	10
Interest Rate (%) =	10
Capital Recovery Factor =	0.163
Capital Recovery Costs ($/yr) =	86,739
Taxes, Insurance, G&A ($) =	38,707
TOTAL ANNUALIZED COST ($)	319,485
Controlled emissions (tpy)	64
Cost effectiveness ($/ton)	5,031

Recovery Credit Based on Fuel Use to Replace No. 2 Fuel Oil

Recovered Solvent (gal/yr) =	16,663
Fuel Value of Rec. Solvent ($/gal) =	1.00
Fuel Value of Rec. Solvent ($/yr) =	16,663

Recovery Credit Based on Fuel Use to Replace Natural Gas

Recovered Solvent (lb/yr)	116,640
Fuel Value of Rec. Solvent ($/lb) =	0.049
Fuel Value of Rec. Solvent ($/yr) =	5,684

Controlled Emissions (tpy)	58
Cost effectiveness($/ton) (based on recovery value)	1,484
Cost effectiveness($/ton) (based on fuel value-No. 2 Fuel Oil)	1,898
Cost effectiveness($/ton) (based on fuel value-Natural Gas)	2,086

APPENDIX C-3. EPS BEAD PRODUCTION MODEL FACILITY (4500 TPY CAPACITY)

CARBON ADSORPTION COST ESTIMATION

DESIGN BASIS

Maximum Total Flow (cfm)	10,593
Total Solvent Usage (lbs/year)	540,000
Production Losses (%)	60
Capture Efficiency (%)	60
Control Efficiency (%)	90

Blowing Agent	Avg. Loading (lbs/hr)	Gas Conc. (ppm)	MW	Working Cap. (lb/lb of C)
Pentane	21	177	72	0.045

Adsorption Time (hrs) =	12
Desorption Time (hrs) =	1.5
Number of Beds Adsorbing =	2
Number of Beds Desorbing =	1
Total Number of Beds =	3
Carbon Requirement (lbs) =	8,331
Superficial Bed Vel. (ft/min) =	100
Carbon Bed Diameter (ft) =	6.66
Carbon Bed Length (ft) =	7.95
Carbon Bed Surface Area (ft^2) =	236

INSTALLED COST

Carbon Cost ($) =	16,663
Vessel Cost ($) =	19,013
Additional Duct Length (ft) =	1,000
Additional Duct ($) =	67,097
Total Equipment Cost ($) =	192,142
Total Purchased Equip. Cost ($) =	226,728
Installation Direct Costs ($) =	68,018
Total Direct Costs($) =	294,746
Total Indirect Costs ($) =	115,631

THERMAL INCINERATION COST ANALYSIS

DESIGN BASIS

Maximum Total Flow (cfm)	10,593
Total Solvent Usage (lbs/year)	540,000
Production Losses (%)	60
Capture Efficiency (%)	60
Control Efficiency (%)	98

Blowing Agent	Avg. Loading (lbs/hr)	Gas Conc. (ppm)	MW	Heat of Combustion (BTU/lb)
Pentane	21	177	72	9

Incinerator Operating Temperature (F)	1,600
Fractional Energy Recovery =	0.70
Preheater Inlet Temperature (F) =	77
Preheater Outlet Temperature (F) =	1,143
Flue Gas Outlet Temperature (F) =	534
Auxilliary Fuel Requirements (scfm) =	138
Total Flow Rate =	10,731

INSTALLED COST

Equipment Cost ($) =	217,220
Additional Duct Length (ft) =	1,000
Additional Duct ($) =	67,097
Total Equipment Cost ($) =	284,317
Total Purchased Equip. Cost ($) =	335,494
Installation Direct Costs ($) =	100,648
Total Direct Costs ($) =	436,142
Total Indirect Costs ($) =	171,102
Total Capital Investment ($) =	607,244

ANNUAL COSTS

Total Capital Investment ($) =	410,377

ANNUAL COSTS

Steam Requirement (lbs/year) =	612,360
Steam Cost ($/1000 lbs) =	6.00
Steam Costs ($/year) =	3,674
Cooling Water Req. (gal/yr) =	2,100,395
Cooling Water Cost ($/1000 gal) =	0.20
Cooling Water Cost ($/yr) =	420
HF Electricity Req. (Kw-hr/yr) =	16,618
DF Electricity Req. (Kw-hr/yr) =	735
CW Electricity Req. (Kw-hr/yr) =	41,213
Total Elec. Req. (Kw-hr/yr) =	58,565
Electricity Cost ($/Kw-hr) =	0.06
Electricity Cost ($/yr) =	3,514
Carbon Replacement Cost ($) =	4,857
Operating Labor (hrs/yr) =	604
Labor Cost ($/hr) =	15
Operating Labor Cost ($/yr) =	9,056
Maintenace Labor & Mat. ($/yr) =	19,924
Total Direct Costs ($/yr) =	41,445
Equipment Life (yrs) =	10
Interest Rate (%) =	10
Capital Recovery Factor =	0.163
Capital Recovery Costs ($/yr) =	63,068
Taxes, Insurance, G&A ($) =	33,803
TOTAL ANNUALIZED COST ($) =	138,316

Recovery Credit Based on Reuse

Recovered Solvent (lb/yr)	174,960
Reuse Value of Rec. Solvent ($/lb) =	0.35
Reuse Value of Rec. Solvent ($/yr) =	61,236
Power Fan Elc. (kW-hr/yr)	319,602
Electricity Cost ($/kW-hr)	0.06
Electricity Cost ($) =	19,176
Auxiliary Fuel Consumption (scfm) =	138
Auxiliary Fuel Cost ($/scf) =	0.0033
Auxiliary Fuel Cost ($) =	229,815
Operating Labor (hrs/yr)	604
Labor Cost ($/hr) =	15
Operating Labor Cost ($/yr)	9,056
Maintenance Labor & Mat. ($/yr) =	19,924
Total Direct Costs ($/yr) =	277,971
Equipment Life (yrs) =	10
Interest Rate (%) =	10
Capital Recovery Factor =	0.163
Capital Recovery Costs ($/yr) =	98,826
Taxes, Insurance, G&A ($) =	41,678
TOTAL ANNUALIZED COST ($)	418,475
Controlled emissions (tpy)	95
Cost effectiveness ($/ton)	4,393

Recovery Credit Based on Fuel Use to Replace No. 2 Fuel Oil

Recovered Solvent (gal/yr) =	24,994
Fuel Value of Rec. Solvent ($/gal) =	1.00
Fuel Value of Rec. Solvent ($/yr) =	24,994

Recovery Credit Based on Fuel Use to Replace Natural Gas

Recovered Solvent (lb/yr)	174,960
Fuel Value of Rec. Solvent ($/lb) =	0.049
Fuel Value of Rec. Solvent ($/yr) =	8,526

Controlled Emissions (tpy)	87
Cost effectiveness($/ton) (based on recovery value)	881
Cost effectiveness($/ton) (based on fuel value-No. 2 Fuel Oil)	1,295
Cost effectiveness($/ton) (based on fuel value-Natural Gas)	1,484

APPENDIX C-4. PSF SHEET PRODUCTION MODEL FACILITY (1000 TPY CAPACITY)

CARBON ADSORPTION COST ESTIMATION

DESIGN BASIS

Maximum Total Flow (cfm)	3,000
Total Solvent Usage (lbs/year)	96,000
Production Losses (%)	60
Capture Efficiency (%)	60
Control Efficiency (%)	90

Blowing Agent	Avg. Loading (lbs/hr)	Gas Conc. (ppm)	MW	Working Cap. (lb/lb of C)
Pentane	4	111	72	0.045

Adsorption Time (hrs) =	16
Desorption Time (hrs) =	1.5
Number of Beds Adsorbing =	2
Number of Beds Desorbing =	1
Total Number of Beds =	3
Carbon Requirement (lbs) =	1,975
Superficial Bed Vel. (ft/min) =	90
Carbon Bed Diameter (ft) =	4.61
Carbon Bed Length (ft) =	5.32
Carbon Bed Surface Area (ft^2) =	110

INSTALLED COST

Carbon Cost ($) =	3,950
Vessel Cost ($) =	10,519
Additional Duct Length (ft) =	1,000
Additional Duct ($) =	33,471
Total Equipment Cost ($) =	104,723
Total Purchased Equip. Cost ($) =	123,574
Installation Direct Costs ($) =	37,072
Total Direct Costs($) =	160,646

THERMAL INCINERATION COST ANALYSIS

DESIGN BASIS

Maximum Total Flow (cfm)	3,000
Total Solvent Usage (lbs/year)	96,000
Production Losses (%)	60
Capture Efficiency (%)	60
Control Efficiency (%)	98

Blowing Agent	Avg. Loading (lbs/hr)	Gas Conc. (ppm)	MW	Heat of Combustion (BTU/lb)	T avg. = 1372 C(77) = 0.24 C(T)= 0.29
Pentane	4	111	72	5	Avg. C = 0.26

Incinerator Operating Temperature (F)	1,600
Fractional Energy Recovery =	0.70
Preheater Inlet Temperature (F) =	77
Preheater Outlet Temperature (F) =	1,143
Flue Gas Outlet Temperature (F) =	534
Auxilliary Fuel Requirements (scfm) =	40
Total Flow Rate =	3,039

INSTALLED COST

Equipment Cost ($) =	158,466
Additional Duct Length (ft) =	1,000
Additional Duct ($) =	33,660
Total Equipment Cost ($) =	192,126
Total Purchased Equip. Cost ($) =	226,709
Installation Direct Costs ($) =	68,013
Total Direct Costs ($) =	294,721
Total Indirect Costs ($) =	115,621
Total Capital Investment ($) =	410,343

Total Indirect Costs ($) =	63,023
Total Capital Investment ($) =	223,668

ANNUAL COSTS

Steam Requirement (lbs/year) =	108,864
Steam Cost ($/1000 lbs) =	6.00
Steam Costs ($/year) =	653
Cooling Water Req. (gal/yr) =	373,404
Cooling Water Cost ($/1000 gal) =	0.20
Cooling Water Cost ($/yr) =	75
MF Electricity Req. (Kw-hr/yr) =	30,659
DF Electricity Req. (Kw-hr/yr) =	841
CW Electricity Req. (Kw-hr/yr) =	7,327
Total Elec. Req. (Kw-hr/yr) =	38,827
Electricity Cost ($/Kw-hr) =	0.06
Electricity Cost ($/yr) =	2,330
Carbon Replacement Cost ($) =	1,151
Operating Labor (hrs/yr) =	604
Labor Cost ($/hr) =	15
Operating Labor Cost ($/yr) =	9,056
Maintenace Labor & Mat. ($/yr) =	19,924
Total Direct Costs ($/yr) =	33,189
Equipment Life (yrs) =	10
Interest Rate (%) =	10
Capital Recovery Factor =	0.163
Capital Recovery Costs ($/yr) =	35,519
Taxes, Insurance, G&A ($) =	26,335
TOTAL ANNUALIZED COST ($) =	95,043

Recovery Credit Based on Reuse

Recovered Solvent (lb/yr)	31,104
Reuse Value of Rec. Solvent ($/lb) =	0.35
Reuse Value of Rec. Solvent ($/yr) =	10,886

ANNUAL COSTS

Power Fan Elc. (kW-hr/yr)	90,522
Electricity Cost ($/kW-hr)	0.06
Electricity Cost ($) =	5,431
Auxiliary Fuel Consumption (scfm) =	40
Auxiliary Fuel Cost ($/scf) =	0.0033
Auxiliary Fuel Cost ($) =	66,454
Operating Labor (hrs/yr)	604
Labor Cost ($/hr) =	15
Operating Labor Cost ($/yr)	9,056
Maintenance Labor & Mat. ($/yr) =	19,924
Total Direct Costs ($/yr) =	100,865
Equipment Life (yrs) =	10
Interest Rate (%) =	10
Capital Recovery Factor =	0.163
Capital Recovery Costs ($/yr) =	66,781
Taxes, Insurance, G&A ($) =	33,802
TOTAL ANNUALIZED COST ($)	201,448
Controlled emissions (tpy)	17
Cost effectiveness ($/ton)	11,896

Recovery Credit Based on Fuel Use to Replace No. 2 Fuel Oil	
Recovered Solvent (gal/yr) =	4,443
Fuel Value of Rec. Solvent ($/gal) =	1.00
Fuel Value of Rec. Solvent ($/yr) =	4,443
Recovery Credit Based on Fuel Use to Replace Natural Gas	
Recovered Solvent (lb/yr)	31,104
Fuel Value of Rec. Solvent ($/lb) =	0.049
Fuel Value of Rec. Solvent ($/yr) =	1,516
Controlled Emissions (tpy)	16
Cost effectiveness($/ton) (based on recovery value)	5,411
Cost effectiveness($/ton) (based on fuel value-No. 2 Fuel Oil)	5,826
Cost effectiveness($/ton) (based on fuel value-Natural Gas)	6,014

APPENDIX C-5. PSF SHEET PRODUCTION MODEL FACILITY (5000 TPY CAPACITY)

CARBON ADSORPTION COST ESTIMATION

DESIGN BASIS

Maximum Total Flow (cfm)	15,426
Total Solvent Usage (lbs/year)	480,000
Production Losses (%)	60
Capture Efficiency (%)	60
Control Efficiency (%)	90

Blowing Agent	Avg. Loading (lbs/hr)	Gas Conc. (ppm)	MW	Working Cap. (lb/lb of C)
Pentane	19	108	72	0.045

Adsorption Time (hrs) =	16
Desorption Time (hrs) =	1.5
Number of Beds Adsorbing =	2
Number of Beds Desorbing =	1
Total Number of Beds =	3
Carbon Requirement (lbs) =	9,874
Superficial Bed Vel. (ft/min) =	90
Carbon Bed Diameter (ft) =	4.88
Carbon Bed Length (ft) =	17.56
Carbon Bed Surface Area (ft^2) =	306

INSTALLED COST

Carbon Cost ($) =	19,749
Vessel Cost ($) =	23,301
Additional Duct Length (ft) =	1,000
Additional Duct ($) =	82,539
Total Equipment Cost ($) =	227,232
Total Purchased Equip. Cost ($) =	268,133
Installation Direct Costs ($) =	80,440
Total Direct Costs($) =	348,573

THERMAL INCINERATION COST ANALYSIS

DESIGN BASIS

Maximum Total Flow (cfm)	15,426
Total Solvent Usage (lbs/year)	480,000
Production Losses (%)	60
Capture Efficiency (%)	60
Control Efficiency (%)	98

Blowing Agent	Avg. Loading (lbs/hr)	Gas Conc. (ppm)	MW	Heat of Combustion (BTU/lb)
Pentane	19	108	72	5

T avg. = 1372
C(77) = 0.24
C(T)= 0.29
Avg. C = 0.26

Incinerator Operating Temperature (F)	1,600
Fractional Energy Recovery =	0.70
Preheater Inlet Temperature (F) =	77
Preheater Outlet Temperature (F) =	1,143
Flue Gas Outlet Temperature (F) =	534
Auxilliary Fuel Requirements (scfm) =	206
Total Flow Rate =	15,632

INSTALLED COST

Equipment Cost ($) =	238,637
Additional Duct Length (ft) =	1,000
Additional Duct ($) =	83,112
Total Equipment Cost ($) =	321,749
Total Purchased Equip. Cost ($) =	379,664
Installation Direct Costs ($) =	113,899
Total Direct Costs ($) =	493,563
Total Indirect Costs ($) =	193,629
Total Capital Investment ($) =	687,192

Total Indirect Costs ($) =	136,748
Total Capital Investment ($) =	485,321

ANNUAL COSTS

Steam Requirement (lbs/year) =	544,320
Steam Cost ($/1000 lbs) =	6.00
Steam Costs ($/year) =	3,266
Cooling Water Req. (gal/yr) =	1,867,018
Cooling Water Cost ($/1000 gal) =	0.20
Cooling Water Cost ($/yr) =	373
MF Electricity Req. (Kw-hr/yr) =	24,187
DF Electricity Req. (Kw-hr/yr) =	652
CV Electricity Req. (Kw-hr/yr) =	36,633
Total Elec. Req. (Kw-hr/yr) =	61,473
Electricity Cost ($/Kw-hr) =	0.06
Electricity Cost ($/yr) =	3,688
Carbon Replacement Cost ($) =	5,757
Operating Labor (hrs/yr) =	604
Labor Cost ($/hr) =	15
Operating Labor Cost ($/yr) =	9,056
Maintenace Labor & Mat. ($/yr) =	19,924
Total Direct Costs ($/yr) =	42,064
Equipment Life (yrs) =	10
Interest Rate (%) =	10
Capital Recovery Factor =	0.163
Capital Recovery Costs ($/yr) =	74,576
Taxes, Insurance, G&A ($) =	36,801
TOTAL ANNUALIZED COST ($) =	153,441

Recovery Credit Based on Reuse

Recovered Solvent (lb/yr)	155,520
Reuse Value of Rec. Solvent ($/lb) =	0.35
Reuse Value of Rec. Solvent ($/yr) =	54,432

ANNUAL COSTS

Power Fan Elc. (kW-hr/yr)	465,546
Electricity Cost ($/kW-hr)	0.06
Electricity Cost ($) =	27,933
Auxiliary Fuel Consumption (scfm) =	206
Auxiliary Fuel Cost ($/scf) =	0.0033
Auxiliary Fuel Cost ($) =	342,095
Operating Labor (hrs/yr)	604
Labor Cost ($/hr) =	15
Operating Labor Cost ($/yr)	9,056
Maintenance Labor & Mat. ($/yr) =	19,924
Total Direct Costs ($/yr) =	399,008
Equipment Life (yrs) =	10
Interest Rate (%) =	10
Capital Recovery Factor =	0.163
Capital Recovery Costs ($/yr) =	111,837
Taxes, Insurance, G&A ($) =	44,876
TOTAL ANNUALIZED COST ($)	555,721
Controlled emissions (tpy)	85
Cost effectiveness ($/ton)	6,563

Recovery Credit Based on Fuel Use to Replace No. 2 Fuel Oil

Recovered Solvent (gal/yr) =	22,217
Fuel Value of Rec. Solvent ($/gal) =	1.00
Fuel Value of Rec. Solvent ($/yr) =	22,217

Recovery Credit Based on Fuel Use to Replace Natural Gas

Recovered Solvent (lb/yr)	155,520
Fuel Value of Rec. Solvent ($/lb) =	0.049
Fuel Value of Rec. Solvent ($/yr) =	7,579

Controlled Emissions (tpy)	78
Cost effectiveness($/ton) (based on recovery value)	1,273
Cost effectiveness($/ton) (based on fuel value-No. 2 Fuel Oil)	1,688
Cost effectiveness($/ton) (based on fuel value-Natural Gas)	1,876

APPENDIX C-6. PSF SHEET PRODUCTION MODEL FACILITY (10,500 TPY CAPACITY)

CARBON ADSORPTION COST ESTIMATION

DESIGN BASIS

Maximum Total Flow (cfm)	32,352
Total Solvent Usage (lbs/year)	1,008,000
Production Losses (%)	60
Capture Efficiency (%)	60
Control Efficiency (%)	90

Blowing Agent	Avg. Loading (lbs/hr)	Gas Conc. (ppm)	MW	Working Cap. (lb/lb of C)
Pentane	39	108	72	0.045

Adsorption Time (hrs) =	16
Desorption Time (hrs) =	1.5
Number of Beds Adsorbing =	2
Number of Beds Desorbing =	1
Total Number of Beds =	3
Carbon Requirement (lbs) =	20,736
Superficial Bed Vel. (ft/min) =	90
Carbon Bed Diameter (ft) =	4.88
Carbon Bed Length (ft) =	36.78
Carbon Bed Surface Area (ft^2) =	602

INSTALLED COST

Carbon Cost ($) =	41,472
Vessel Cost ($) =	39,391
Additional Duct Length (ft) =	1,000
Additional Duct ($) =	124,502
Total Equipment Cost ($) =	357,990
Total Purchased Equip. Cost ($) =	422,428
Installation Direct Costs ($) =	126,728
Total Direct Costs($) =	549,157

THERMAL INCINERATION COST ANALYSIS

DESIGN BASIS

Maximum Total Flow (cfm)	32,352
Total Solvent Usage (lbs/year)	1,008,000
Production Losses (%)	60
Capture Efficiency (%)	60
Control Efficiency (%)	98

Blowing Agent	Avg. Loading (lbs/hr)	Gas Conc. (ppm)	MW	Heat of Combustion (BTU/lb)
Pentane	39	108	72	5

T avg. = 1372
C(77) = 0.24
C(T)= 0.29
Avg. C = 0.26

Incinerator Operating Temperature (F)	1,600
Fractional Energy Recovery =	0.70
Preheater Inlet Temperature (F) =	77
Preheater Outlet Temperature (F) =	1,143
Flue Gas Outlet Temperature (F) =	534
Auxilliary Fuel Requirements (scfm) =	431
Total Flow Rate =	32,783

INSTALLED COST

Equipment Cost ($) =	287,177
Additional Duct Length (ft) =	1,000
Additional Duct ($) =	125,439
Total Equipment Cost ($) =	412,615
Total Purchased Equip. Cost ($) =	486,886
Installation Direct Costs ($) =	146,066
Total Direct Costs ($) =	632,952
Total Indirect Costs ($) =	248,312
Total Capital Investment ($) =	881,263

Total Indirect Costs ($) =	215,438
Total Capital Investment ($) =	764,595

ANNUAL COSTS

Steam Requirement (lbs/year) =	1,143,072
Steam Cost ($/1000 lbs) =	6.00
Steam Costs ($/year) =	6,858
Cooling Water Req. (gal/yr) =	3,920,737
Cooling Water Cost ($/1000 gal) =	0.20
Cooling Water Cost ($/yr) =	784
MF Electricity Req. (Kw-hr/yr) =	50,726
DF Electricity Req. (Kw-hr/yr) =	1,369
CW Electricity Req. (Kw-hr/yr) =	76,930
Total Elec. Req. (Kw-hr/yr) =	129,026
Electricity Cost ($/Kw-hr) =	0.06
Electricity Cost ($/yr) =	7,742
Carbon Replacement Cost ($) =	12,089
Operating Labor (hrs/yr) =	604
Labor Cost ($/hr) =	15
Operating Labor Cost ($/yr) =	9,056
Maintenace Labor & Mat. ($/yr) =	19,924
Total Direct Costs ($/yr) =	56,453
Equipment Life (yrs) =	10
Interest Rate (%) =	10
Capital Recovery Factor =	0.163
Capital Recovery Costs ($/yr) =	115,178
Taxes, Insurance, G&A ($) =	47,972
TOTAL ANNUALIZED COST ($) =	219,603

Recovery Credit Based on Reuse

Recovered Solvent (lb/yr)	326,592
Reuse Value of Rec. Solvent ($/lb) =	0.35
Reuse Value of Rec. Solvent ($/yr) =	114,307

ANNUAL COSTS

Power Fan Elc. (kW-hr/yr)	976,352
Electricity Cost ($/kW-hr)	0.06
Electricity Cost ($) =	58,581
Auxiliary Fuel Consumption (scfm) =	431
Auxiliary Fuel Cost ($/scf) =	0.0033
Auxiliary Fuel Cost ($) =	717,418
Operating Labor (hrs/yr)	604
Labor Cost ($/hr) =	15
Operating Labor Cost ($/yr)	9,056
Maintenance Labor & Mat. ($/yr) =	19,924
Total Direct Costs ($/yr) =	804,979
Equipment Life (yrs) =	10
Interest Rate (%) =	10
Capital Recovery Factor =	0.163
Capital Recovery Costs ($/yr) =	143,422
Taxes, Insurance, G&A ($) =	52,639
TOTAL ANNUALIZED COST ($)	1,001,039
Controlled emissions (tpy)	178
Cost effectiveness ($/ton)	5,630

Recovery Credit Based on Fuel Use to Replace No. 2 Fuel Oil

Recovered Solvent (gal/yr) =	46,656
Fuel Value of Rec. Solvent ($/gal) =	1.00
Fuel Value of Rec. Solvent ($/yr) =	46,656

Recovery Credit Based on Fuel Use to Replace Natural Gas

Recovered Solvent (lb/yr)	326,592
Fuel Value of Rec. Solvent ($/lb) =	0.049
Fuel Value of Rec. Solvent ($/yr) =	15,916

Controlled Emissions (tpy)	163
Cost effectiveness($/ton) (based on recovery value)	645
Cost effectiveness($/ton) (based on fuel value-No. 2 Fuel Oil)	1,059
Cost effectiveness($/ton) (based on fuel value-Natural Gas)	1,247